(NASA-CR-117145) SPACE SHUTTLE AUXILIARY PROPULSION SYSTEM: APS IGNITION SYSTEM Quarterly Technical Progress Report, Nov. 1970 - Jan. 1971 (Rocketdyne) 184 p

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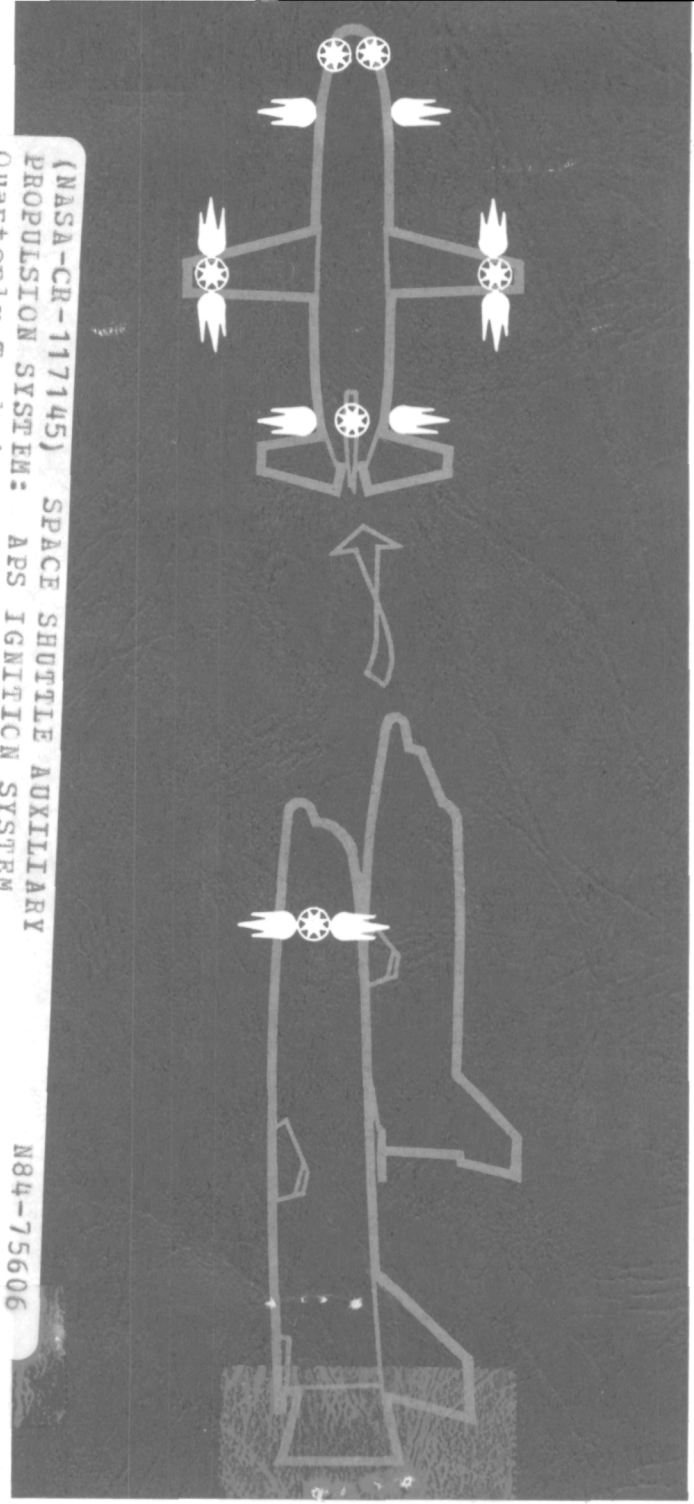

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APS IGNITION SYSTEM QUARTERLY TECHNICAL PROGRESS NARRATIVE

NOVEMBER 1970
JANUARY 1971

Rocketdyne
North American Rockwell

6633 Canoga Avenue,
Canoga Park, California 91304

ASR 71-45

SPACE SHUTTLE AUXILIARY PROPULSION IGNITER SYSTEM

NAS 3-14351

SECOND QUARTERLY TECHNICAL PROGRESS NARRATIVE

NOVEMBER - JANUARY 1971

Prepared for NASA-Lewis Research Center

Cleveland, Ohio 44135

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INTRODUCTION AND SUMMARY

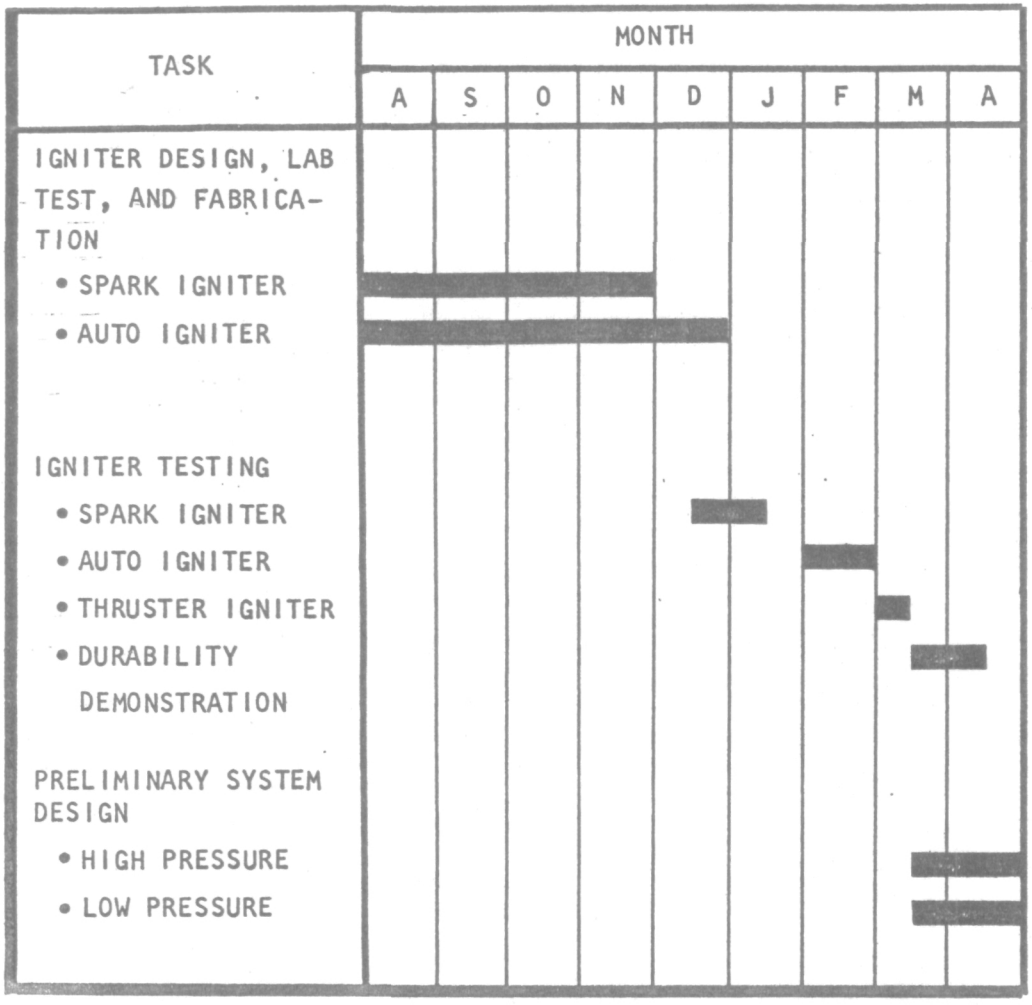
The objective of this program is to obtain basic ignition data on electric spark and resonance tube ignition methods at operating conditions typical of the Space Shuttle APS, and to complete a preliminary design of an optimum ignition system based upon the test results. This technology effort will provide the groundwork input for APS tradeoff studies. It will ensure that specifications established for the APS are realistic and achievable and will provide the basis for an expeditious future engine development program.

The program objectives, scope and schedule are summarized in Fig. 1. This nine-month program consists of parallel efforts at the two chamber pressure levels typical for Space Shuttle APS application, 300 psia (206.9 Newton/cm^2) and 15 psia (10.35 Newton/cm^2). Engine thrust level is 1500 pounds (6672 Newtons). The igniter flowrates are approximately 1 percent of the total thruster propellant flowrate.

The program sequence is shown in Fig. 2. The technical effort is conducted in three tasks: Task I - Igniter Design and Fabrication, Task II - Igniter Tests, and Task III - Ignition System Preliminary Design. Task IV includes program management and reports.

Contract go-ahead was received 23 July 1970 and efforts during the first quarter were devoted primarily to Task I igniter design and fabrication. During the second quarter, igniter hardware fabrication was completed and igniter only testing (Task II) was initiated.

APS IGNITION SYSTEM PROGRAM



OBJECTIVE

- PROVIDE IGNITION SYSTEM FOR LOW AND HIGH PRESSURE APS THRUSTERS
- EVALUATE SPARK IGNITER AND AUTO-IGNITION

SCOPE

- 9 MONTH EFFORT
- LAB TESTS
- IGNITER TESTS
- THRUSTER IGNITIONS
- 2500 CYCLE DURABILITY
- PRELIMINARY SYSTEM DESIGN

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Figure 1

IGNITION SYSTEM PROGRAM SEQUENCE

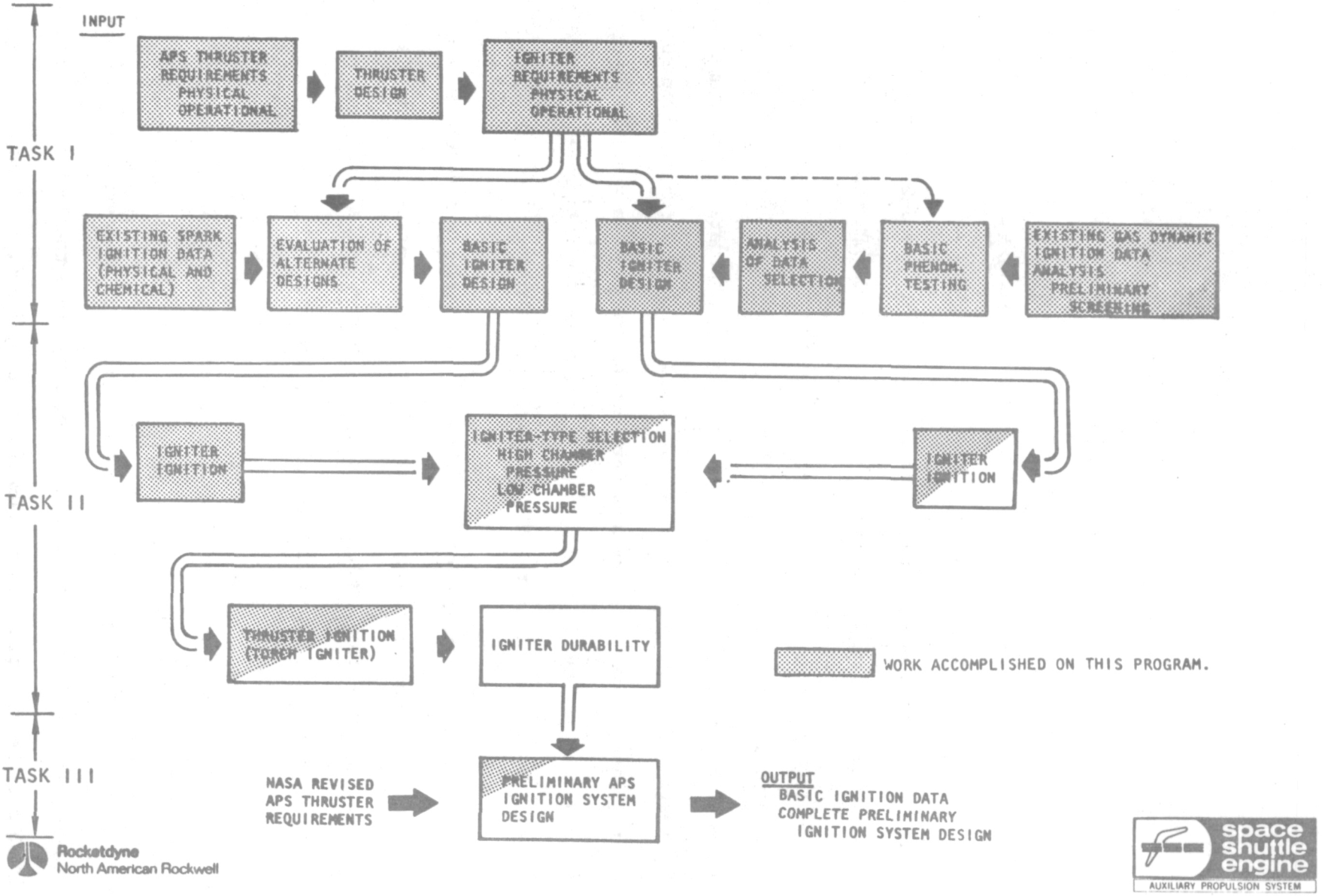


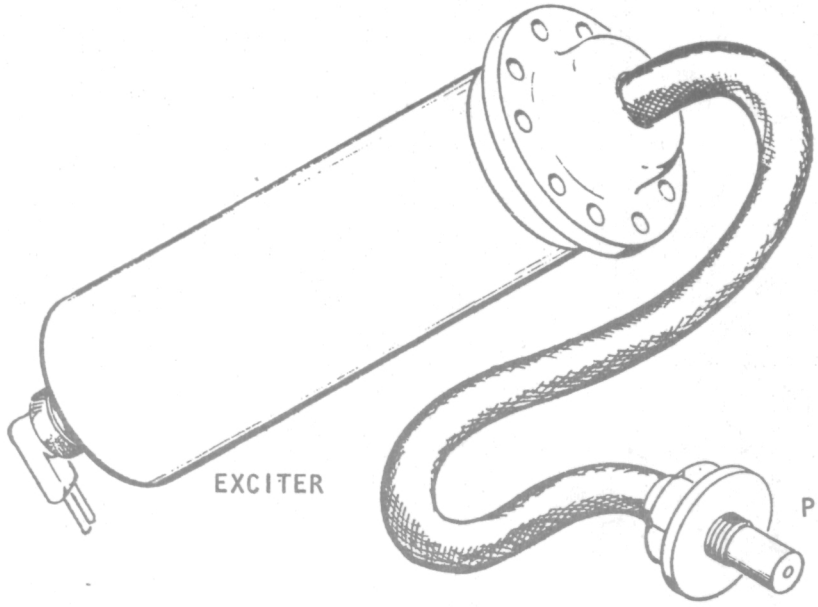
Figure 2

SPARK IGNITER

The principal goal of the spark igniter effort is to reduce the electrical energy requirements to a practical minimum which will enable small, compact, well-shielded exciter and spark plug units to be used. This reduction in energy and size will minimize weight and RFI. Fuel-rich augmented spark igniters have proven reliability (man-rated); however, a reduction in energy level and size and improved packaging are required. The J-2 electrical equipment and the SS/APS unit are shown in Fig. 3. The SS/APS unit is approximately 1.5 inches (3.8 cm) in diameter and approximately 1.5 inches (3.8 cm) long and will accept 28 VDC input. This spark igniter goal is being pursued in a systematic approach of cold flow testing of candidate igniters and laboratory testing of spark plugs in Task I. Early in Task II on "igniter only" testing, energy level requirements were established with a variable energy exciter. During Task II tests, the feasibility of the integrated plug/exciter unit will be demonstrated and RFI data will be obtained.

During the first quarter, the igniter cold flow testing was completed and suitable plug locations have been determined. The high pressure and low pressure igniter designs were completed, submitted, and approved. Fabrication of both igniters was completed during the second quarter. The spark plug and variable energy exciter design and fabrication was also completed. Laboratory testing of five candidate plug tip geometries was conducted and a dual recessed gap type was selected for hot firing evaluation during Task II. During this report period, all high pressure and low pressure spark "igniter only" testing was successfully completed. The igniters and test results are summarized in Fig. 4 and Fig. 5 for the high pressure and low pressure igniters, respectively. The

INTEGRATED APS SPARK PLUG EXCITER
COMPARISON WITH J-2 SPARK EXCITER



PLUG/EXCITER

	J-2	INDUCTIVE
INPUT VDC	28	28
INPUT CURRENT	4.5 AMPERES	<0.5 AMPERES
STORED ENERGY	360 MILLIJOULES	<30 MILLIJOULES
SPARK RATE	50 CPS	200 CPS
WEIGHT, POUNDS	6.0	<0.3
RFI	LARGE UNIT WITH EXTENDED HIGH VOLTAGE CABLE	SMALL WELL-SHIELDED UNIT
	20 DB OVER MIL-I-6181	WILL COMPLY WITH MIL-I-6181
EFFICIENCY	0.28	>0.60

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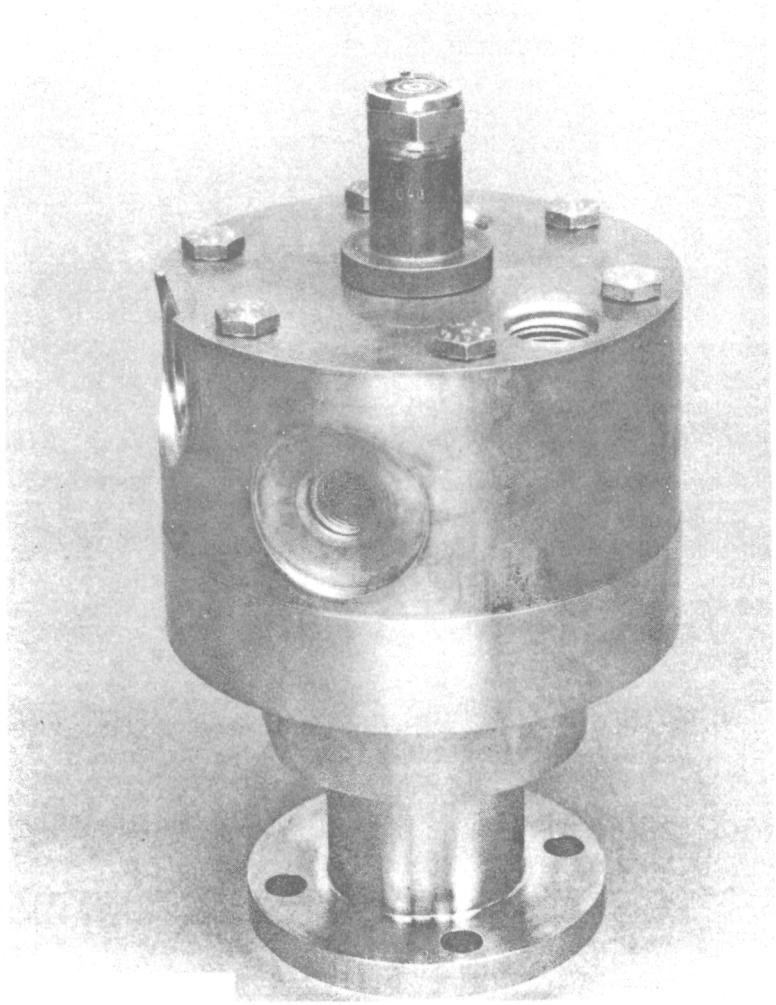
Figure 3

SPARK IGNITER TEST SUMMARY

(HIGH P_c – HOT FIRING)



- 194 TESTS CONDUCTED
- RAPID RESPONSE (.020 - .030 MS)
- LOW ENERGY
- LOW TEMPERATURE (200/300°R)
- INSENSITIVE TO SEQUENCING

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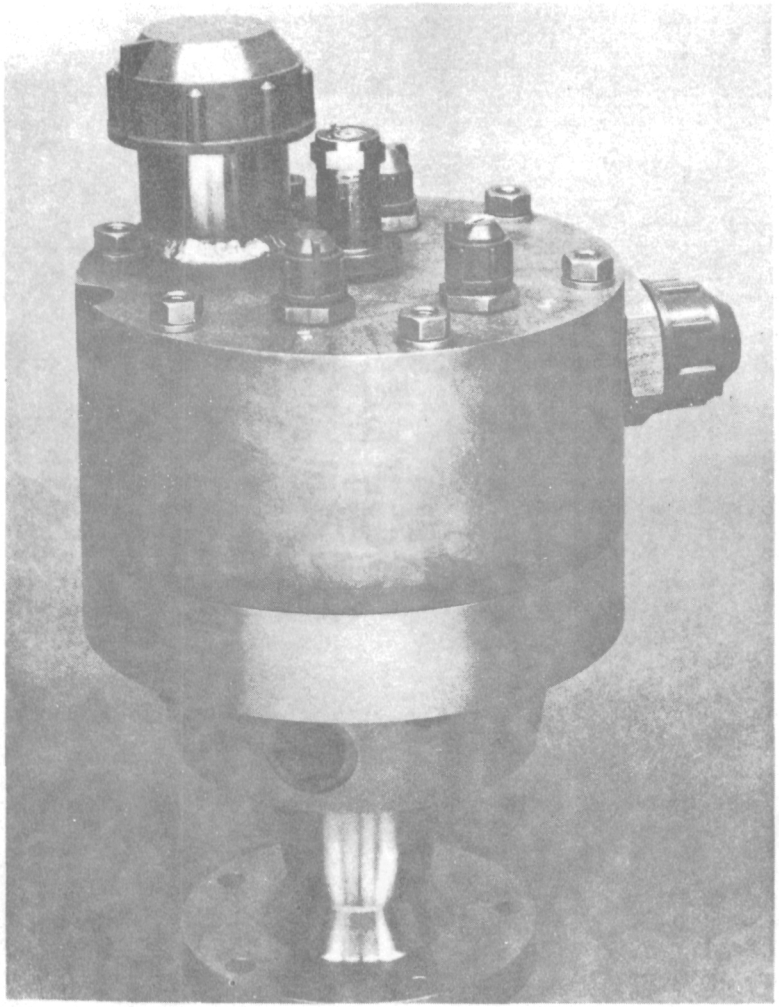
Figure 4

SPARK IGNITER TEST SUMMARY

(LOW P_C — HOT FIRING)



- 103 TESTS CONDUCTED
- RAPID RESPONSE (.020 - .030 MS)
- LOW ENERGY
- LOW TEMPERATURE (200/300°R)
- INSENSITIVE TO SEQUENCING

igniters proved to be insensitive to sequencing and reliable ignitions were obtained over the entire range of propellant inlet conditions. The energy requirements were well below the goal of 30 millijoules for the integrated exciter/spark plug. The design of this unit was completed and fabrication has been initiated.

A test plan for the low pressure igniter/thruster ignition testing was submitted January 1971. (Subsequent to the end of the quarterly report period but during the writing of this report, the low pressure thruster igniter program was successfully completed. Successful ignitions were obtained with spark igniter flowrates down to .01 #/sec or .25% of thruster flowrate. The thruster response from electrical signal to the valve to 90% thruster chamber pressure was also demonstrated by signaling the thruster and igniter valves open simultaneously.)

AUTO IGNITER

The goal of the auto-igniter portion of this program is to demonstrate the feasibility of a new rocket engine ignition device, an auto igniter using a "resonance" phenomena. This device, Fig. 6, operates on gas dynamic principles and requires no external power or catalytic materials. By the proper introduction of the propellants in the auto igniter, the propellants would appear to become hypergolic from a system or vehicle design viewpoint. This auto-igniter goal is being pursued in a systematic approach with cold flow and combustion testing of the basic phenomena during Task I and testing of igniters and igniter/thruster assemblies during Task II.

During the first quarter, the phenomena test hardware was designed, fabricated, and tested. The effects of igniter geometry and operating parameters were evaluated on hydrogen only tests. Combustion tests were also conducted at altitude conditions and with SS/APS igniter flowrates. The feasibility of the igniter concept to provide rapid response (< 0.040 sec) was demonstrated with ambient and cold propellants (~ 250 R).

During the second quarter, the data obtained with the variable geometry test hardware were analyzed and a fixed geometry resonance igniter was designed to interface with the existing Rocketdyne injectors for the Task II testing. The design was approved by NASA and the hardware fabrication was completed. The igniter assembly is shown in Fig. 7. A test plan for the auto-igniter "igniter only" testing was submitted and approved in December. Facility installation and checkout tests were completed in January. (Subsequent to the end of the quarterly report period, but during the writing of this report, the auto-igniter test program was successfully completed. Over 200 tests were conducted

AUTO-IGNITER

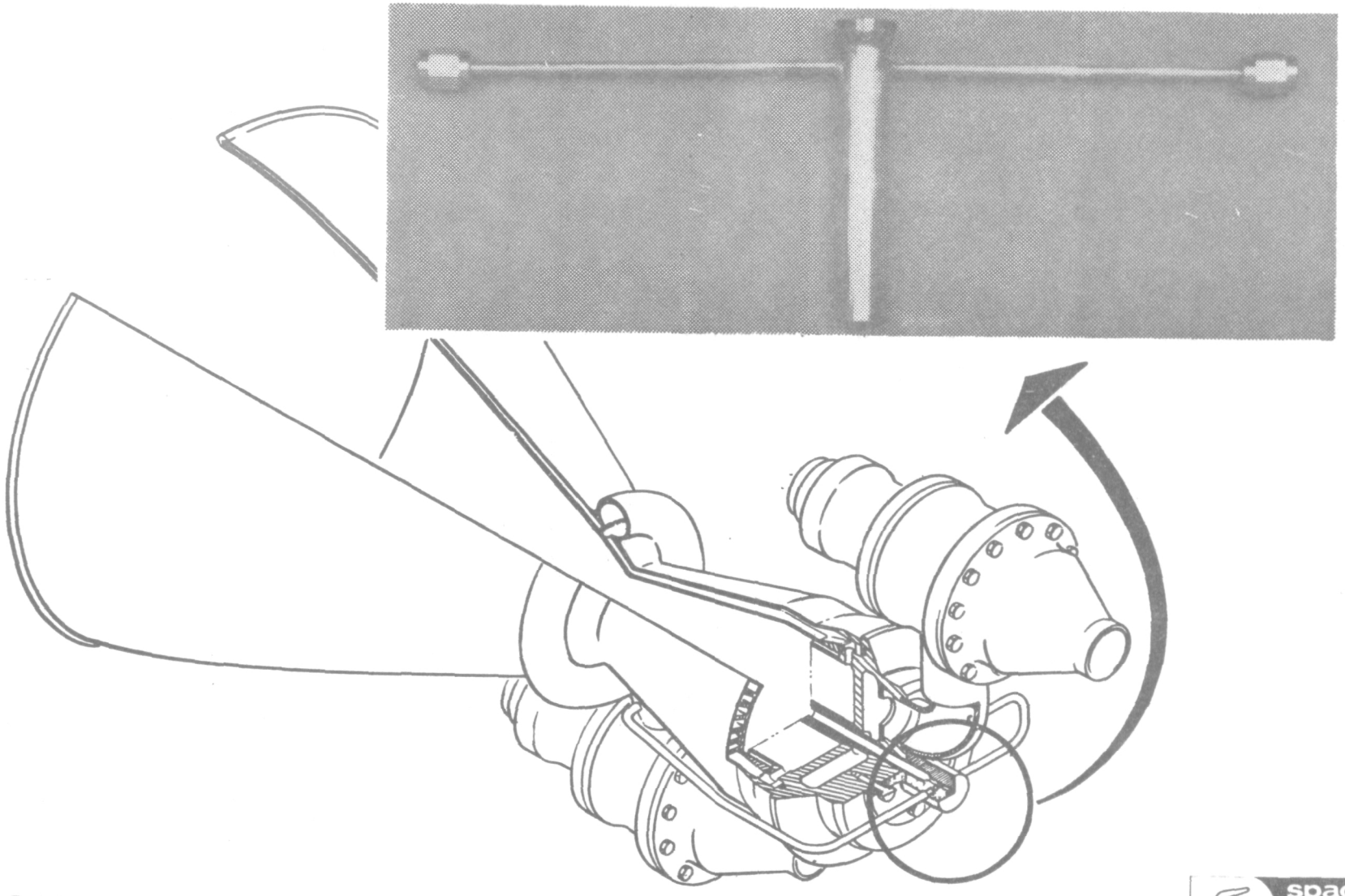


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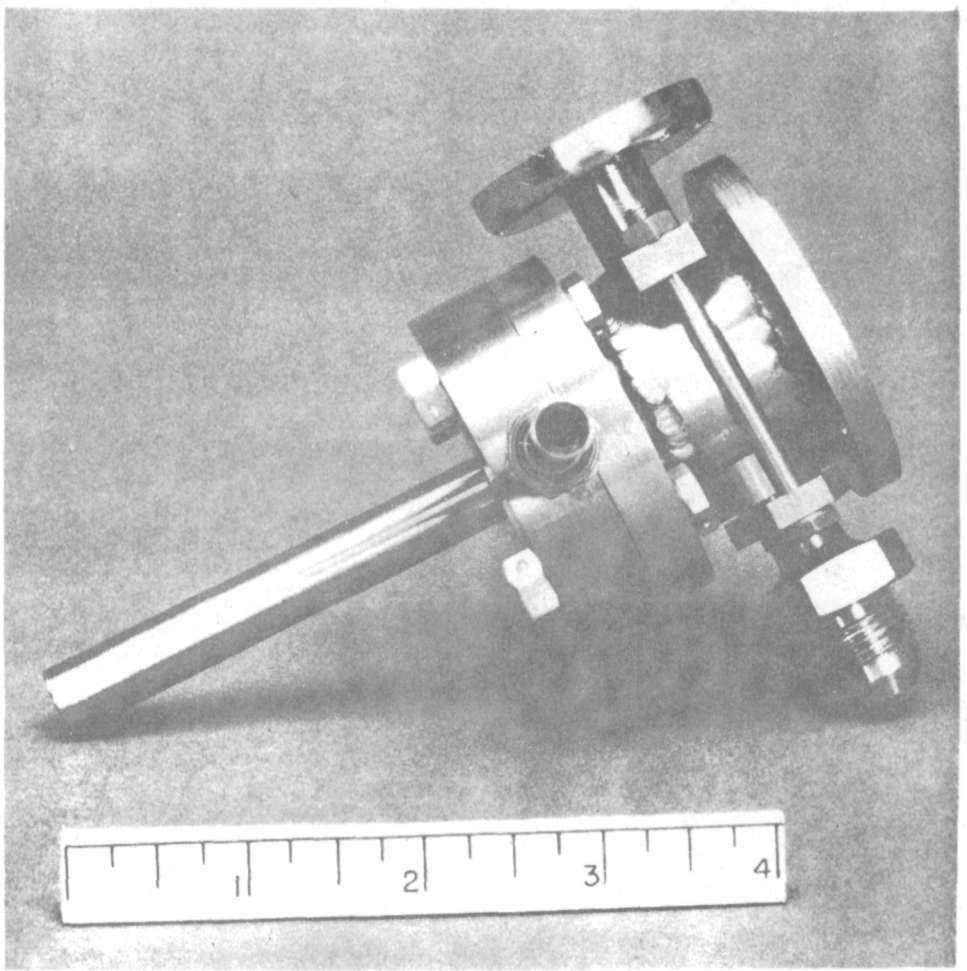
Figure 6

AUTO-IGNITER



- RESONANCE HEATING
- NO EXTERNAL POWER
- RAPID RESPONSE (0.020 - 0.030 MS)
- TESTING IN PROGRESS

Figure 7

demonstrating ignition and sustained combustion over the range of inlet conditions, including cold temperature propellants.)

DESCRIPTION OF PROGRESS

TASK I - IGNITER DESIGN AND FABRICATION

During this task, analysis and design efforts are being conducted for igniters capable of providing reliable ignition for hydrogen/oxygen thrusters operating at the two design points. The efforts on the spark igniter and the auto igniter are being conducted in parallel.

Alternate spark igniter injector and plug location were evaluated on cold flow tests during Task I to obtain a fundamental understanding of mixture ratio and gas velocity at candidate plug locations for the range of operational variables.

Electrical system equipment was also designed, fabricated, and laboratory tested during Task I. This equipment includes a variable energy power supply, spark plugs, and a flight-type fixed-energy integrated plug/converter. The variable energy power supply and different spark plug tip configurations were evaluated by laboratory tests during Task I and were used to establish minimum energy requirements during the initial Task II testing. The design of the flight-type fixed-energy integrated plug/converter has been completed based upon these test results. Fabrication of this unit is in progress.

During Task I, analysis and design efforts were also conducted for resonance igniters capable of providing reliable ignition for hydrogen-oxygen thrusters operating at the two design points.

Basic resonance igniter configurations were established and have been evaluated during Task I on well-instrumented, laboratory-type tests using GH_2/GO_2 propellants. The effects of geometric and operational variables on the ability to obtain elevated temperatures were evaluated during September and the effects of propellant injection, sequencing and propellant temperature on the ability to obtain and sustain combustion were evaluated during October.

The spark igniter designs were submitted for NASA approval and fabrication has been completed.

No effort is planned for the design of the thruster injectors and heat sink thrust chambers. This program will use available Rocketdyne 1500-pound-thrust hardware. A high pressure [300 psia (206.9 Newton/cm^2)] injector and heat sink thrust chamber and a low pressure [15 psia (10.35 Newton/cm^2)] injector and heat sink thrust chamber have been designed, fabricated, and checkout tested.

Task I efforts have been completed with the exception of fabrication of the integrated exciter/spark plug unit. In the following section, the progress during the second quarter on the spark igniter and auto igniter are discussed.

SPARK IGNITER

During this report period, the major Task I effort was devoted to spark igniter fabrication, spark plug laboratory testing, spark plug laboratory test data analysis, and design of the integrated spark plug/exciter unit.

Igniter Fabrication

The igniter designs were submitted and approved in October. Fabrication of the igniters were completed ahead of schedule. The low pressure spark igniter is shown in Fig. 8. The high pressure spark igniter is shown in Fig. 9. These

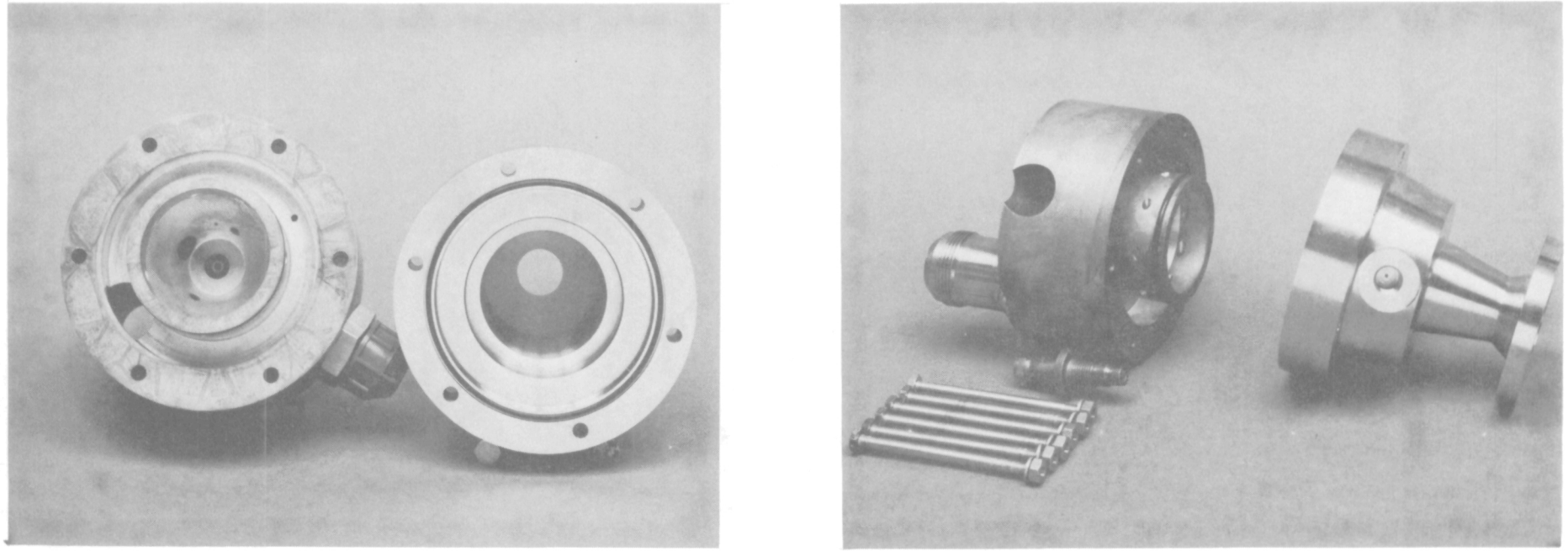


Figure 8. Low Pressure Spark Igniter

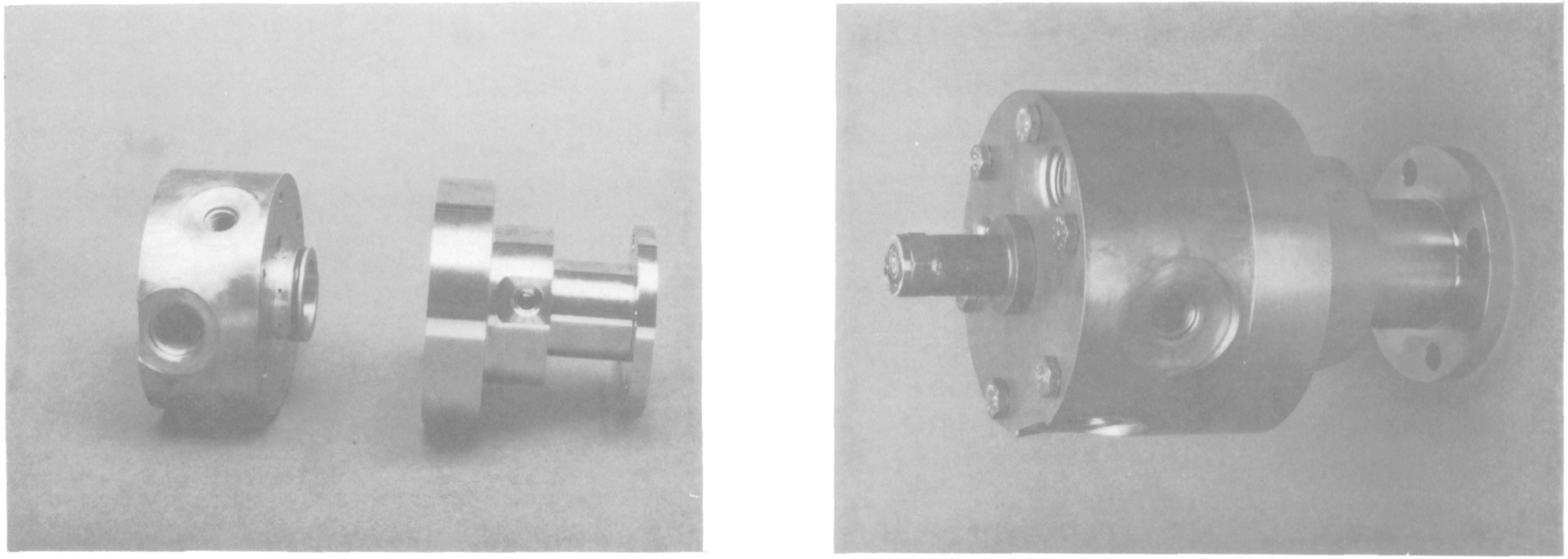


Figure 9. High Pressure Spark Igniter

igniters have been delivered to the test facility for Task II testing.

The initial spark plug characterization tests indicated the 0.025 dual gap (type 4A) spark plug has the most desirable operating characteristics. Therefore, in order to support igniter hot firing tests, an additional Type 4A spark plug was ordered and received from Alberox Corporation.

SPARK PLUG LABORATORY TESTING

Summary

Laboratory characterization testing of candidate spark plug geometries was completed and the resultant data used to select a plug for Task II igniter hot fire tests. The objective of this test series was to select the spark plug geometry (from five basic types) which afforded the best operating parameters influencing the design of the energy conversion system over the operating range (temperature and pressure) anticipated for the APS igniters.

To accomplish this objective, each of the plug types was evaluated in a single spark mode, using an inductive discharge system while varying GN_2 pressure and temperatures at the plug gap. Plugs exhibiting preferred voltage and current characteristics were then tested under similar conditions with repetitive sparks (to a frequency of 200 sparks per second) and a selected plug was re-evaluated with a single spark capacitive discharge system. Attempts were made to photographically record the spark plasma "blossom" emanating from the plug electrode cavities.

Oscilloscope records of the spark discharge voltage and current were analyzed, compiled, and compared with theoretical expectations.

Test Results

The original test plan matrix (First Quarterly Report) was applied and augmented by additional data points suggested by the progressive test results. An indicated in Table 1, a total of 377 tests were conducted at various combinations of spark voltage and energy, temperature and pressure. Five basic plug types, which were further divided into 11 subclasses by gap width variation, were evaluated. Limited data screening indicated that different plug geometries did not yield predictably consistent data, which necessitated the majority of additional test points. Also, a J-2 shunted gap plug was evaluated to assess the effects of the doped surface design feature.

All testing employing the inductive variable energy exciter unit in a single spark mode were successful. Unsatisfactory test data resulted from spark frequency tests, capacitive energy tests, and spark plasma blossom recording attempts. Analysis of these data problems is presented later in this section.

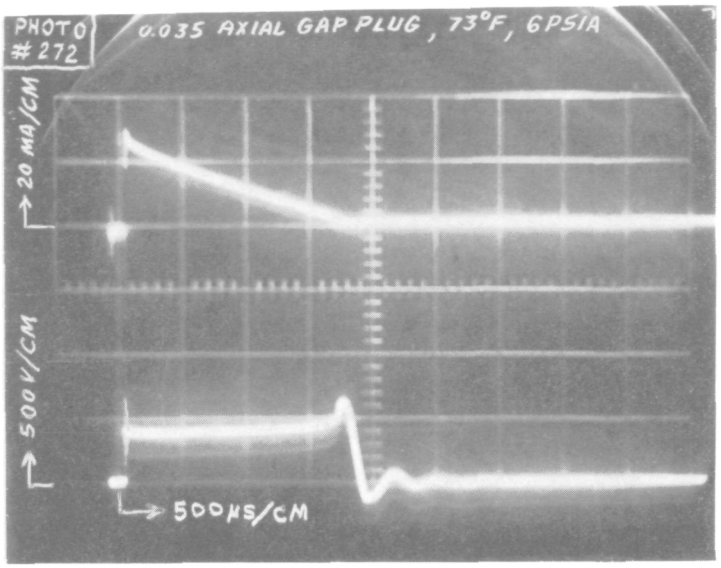
Data Analysis

Typical spark gap current and voltage characteristics are shown in Fig. 10 . All voltage traces indicate an initial high impulse until voltage breakdown occurs, followed by a fairly stable extended period of sustaining voltage during the gap conduction period. A compressed half-sine wave at the conclusion of the discharge represents the reflected voltage of the exciter transformer after the spark plug arc quenches. The typical current trace is a decaying ramp whose initial peak is representative of the transformer energy storage current and whose duration represents the circuit time constant. A steep current "tailoff" at the end of the trace represents the energy dissipated in the exciter transformer after the spark quenches (has insufficient current to maintain conduction).

TABLE 1

SPARK PLUG TEST SUMMARY

Plug Type	Description	Test Pressure Range, psia	Test Temp. Range, F	Polarities	No. Tests
Type 1	0.025 Surface Gap	14.7 to 58.8	-265 to 75	+	58
Type 1A	0.035 Surface Gap	1 to 58.8	-200 to 115	+ & -	29
Type 1B	0.050 Surface Gap	6 to 14.7	75	+	2
Type 2	0.025 Recessed Gap	2 to 230	-265 to 170	+ & -	50
Type 2A	0.035 Recessed Gap	1 to 58.8	-200 to 198	+ & -	31
Type 2B	0.050 Recessed Gap	6 to 29.4	75	+	3
Type 3A	0.025 Dual Surf. Gap	2 to 58.8	-200 to 75	+ & -	85
Type 3B	0.050 Dual Surf. Gap	14.7 to 58.8	75	+ & -	12
Type 4A	0.025 Dual Recessed Gap	1 to 58.8	-200 to 75	+ & -	62
Type 4B	0.050 Dual Recessed Gap	14.7 to 44.1	75	+ & -	21
J-2 Igniter	0.050 Doped Recessed Gap	1 to 58.8	-200 to 75	+	24
					377



0.035 RECESSED AXIAL GAP

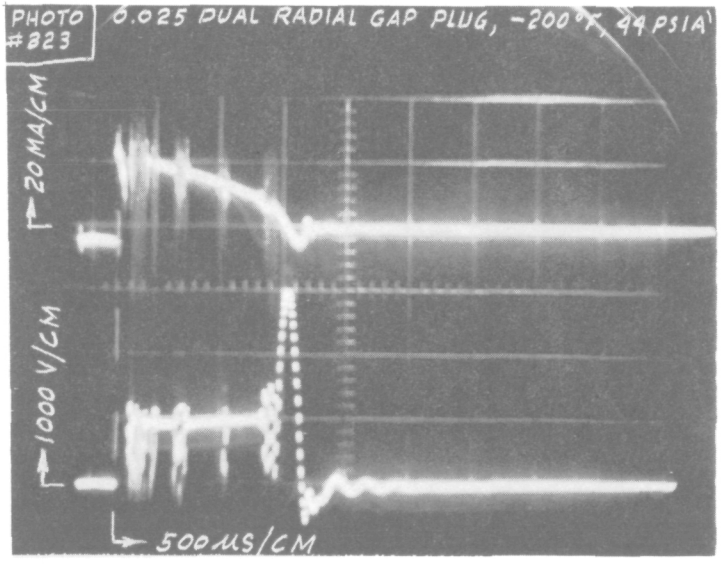


Figure 10. Typical Spark Current and Voltage Characteristics

In Fig. 10, the 0.035-inch recessed axial gap plug traces illustrate an "ideal" record, while those of the 0.025-inch dual radial gap plug illustrate the "noisy traces" often obtained. Noise had no apparent effect on spark visual quality, but contributed an uncertainty in calculating spark energy.

Considering not only spark geometry variables but their influence on design of the integral plug/exciter, the following parametric variables were evaluated as affected by spark gap ambient conditions:

(a) Gap breakdown voltage - dictates the transformer turns ratio, voltage supply and power consumption.

(b) Gap sustaining voltage - determines the spark energy for spark discharge current-time integral and drives transformer efficiency factors through corresponding I^2R losses.

(c) Gap cutoff current - determines the energy loss (remaining stored energy) dissipated following spark quenching.

(d) Spark frequency - may influence gap breakdown and energy characteristics due to residual ionized particles or cathode thermionic emissions.

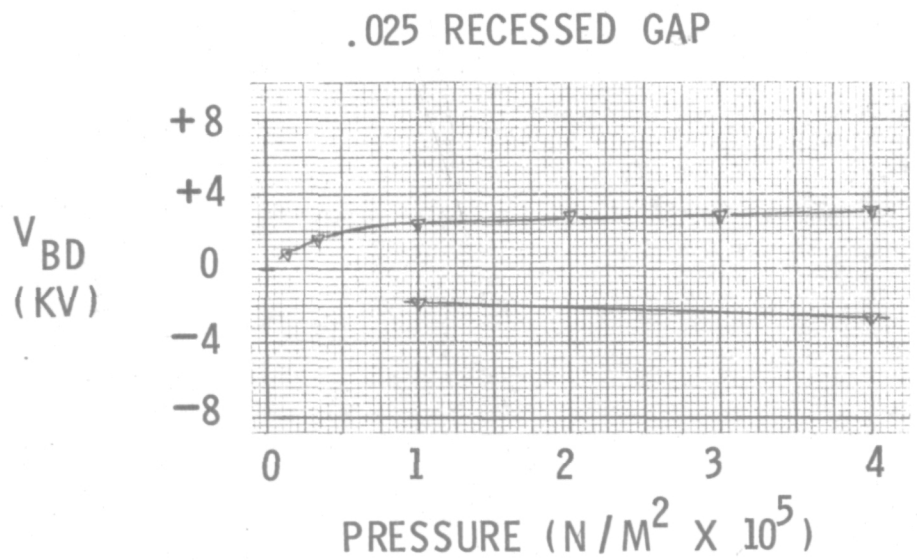
(e) Spark volt-ampere form - determines the type of energy storage system. High current, low voltage discharges typify capacitive systems; low current, high voltage discharges typify inductive systems.

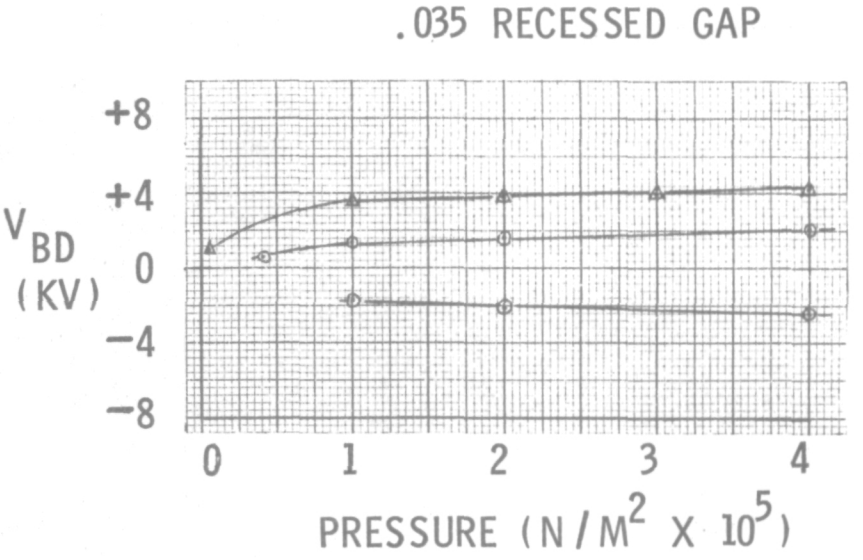
(f) Voltage polarity - influences breakdown voltage, transformer design and electrode erosion.

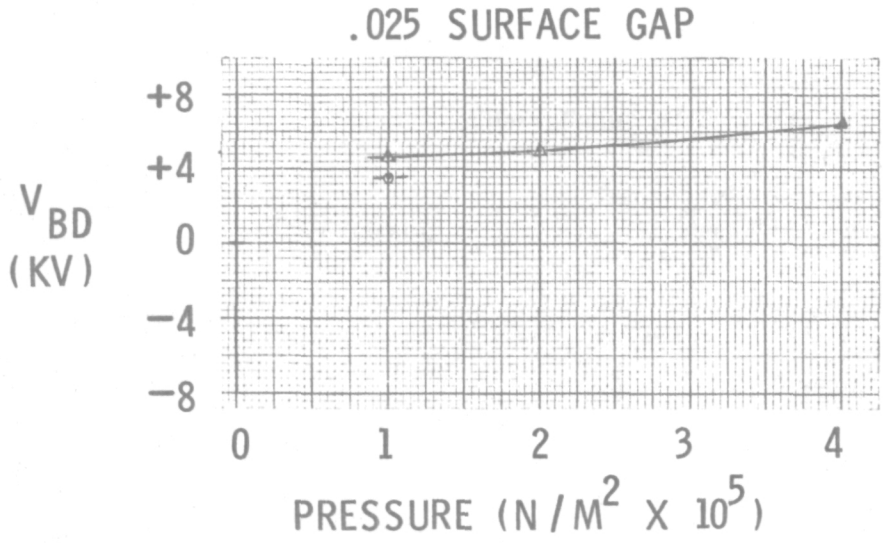
Spark Gap Breakdown Voltage/Polarity

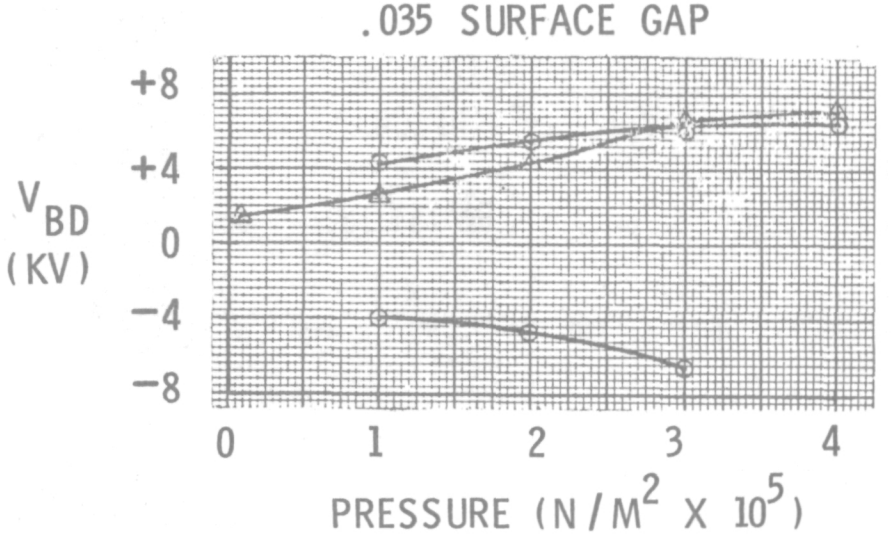
Breakdown voltage as a function of temperature and pressure is plotted for each of the plug types in Figs. 11 through 13. Differences in the number of data points between plugs was generated by both the test matrix and the inability to establish a spark under some conditions. These latter cases were limited to the dual .050-inch gap types (both recessed and surface), in which system energy limitations prevented achievement of sufficient voltage due to transformer inefficiency and saturation at high stored energy/output voltage settings. As it was a design goal to remain below 10 KV ionization volts for the prototype units, and these large dual gap plugs quickly exceeded that level, the missing data points have no program significance.

In general, all small (less than 0.050-inch) plug gaps indicated a divergence from theoretical voltage-pressure relationships. Small, non-uniform gaps may be expected to deviate from Paschen's Law for the following reasons: breakdown voltage characteristics are seriously affected by the lack of uniformity of the electric field. Further, the breakdown voltage for small gaps, particularly at elevated pressures, is limited due to the participation of the electrode material. It can be seen from the breakdown voltage vs pressure characteristics that the 0.025-inch and 0.035-inch gap breakdown voltages (Fig. 11 increase slowly above 1×10^5 N/m^2 pressure, the 0.025-inch dual gap breakdown voltage (Fig. 12) increases slowly above 3×10^5 N/m^2 pressure, while the 0.050-inch gap breakdown voltages do not approach an asymptote within the range of the variables tested. The dual 0.025-inch surface gap plug (Fig. 12) also indicated no stabilization with pressure. This is most likely due to the similarity to a single 0.050-inch surface gap. The breakdown voltage limiting effect of electrode participation is also illustrated by the comparison of the 0.050-inch recessed









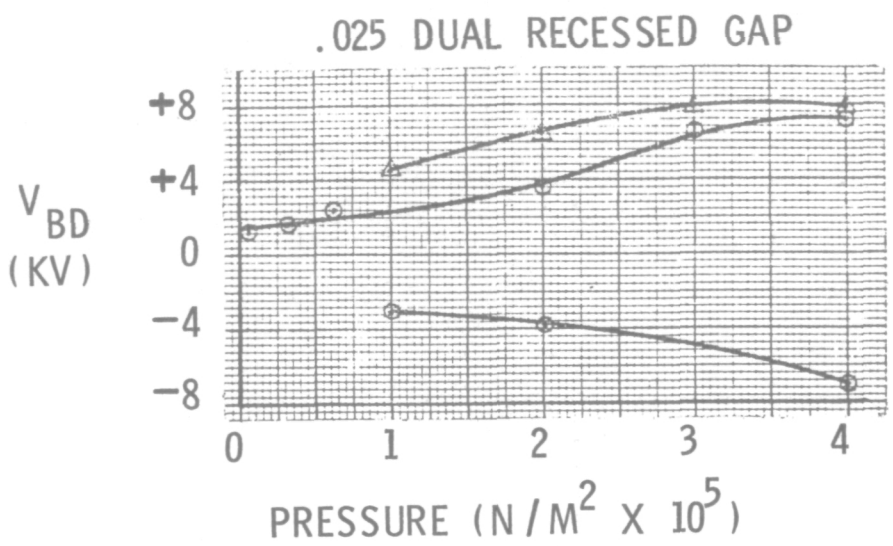
TEMPERATURE LEGEND

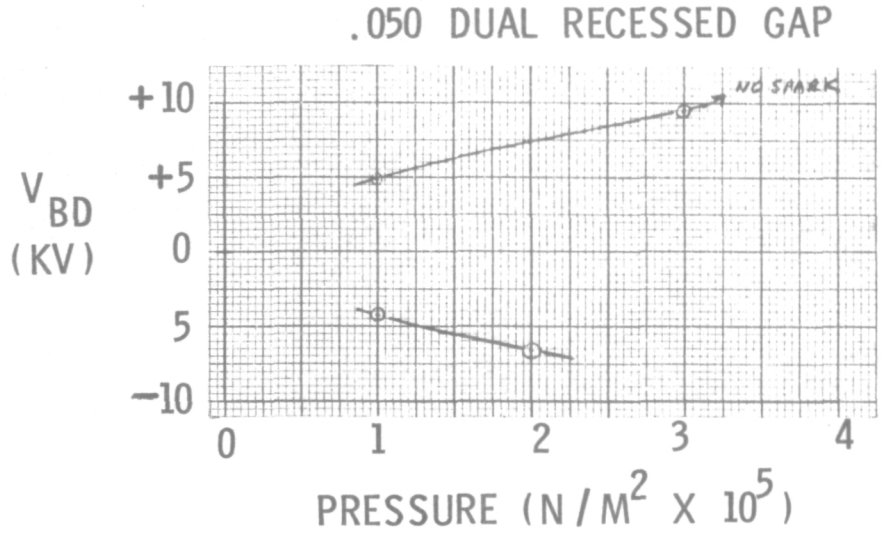
△ — 144° K

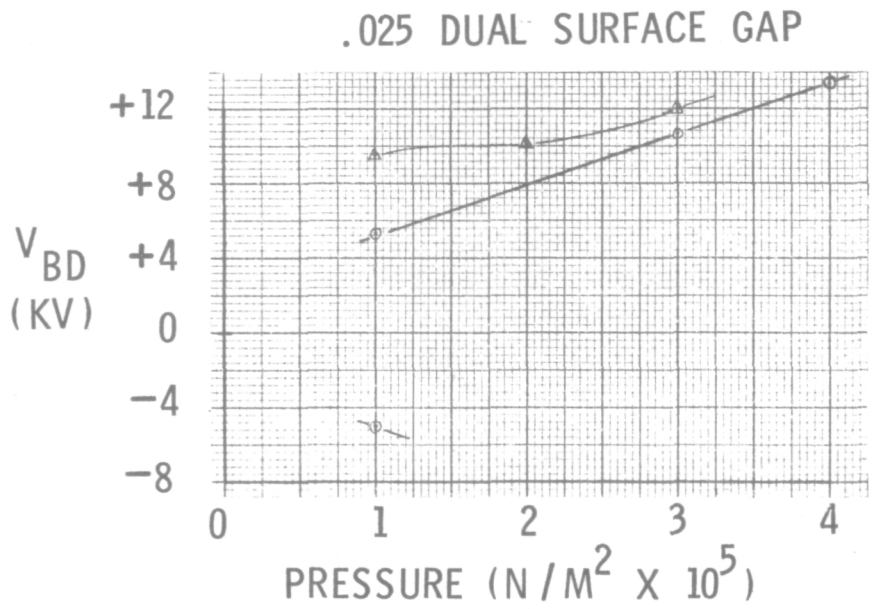
⊙ — 297° K

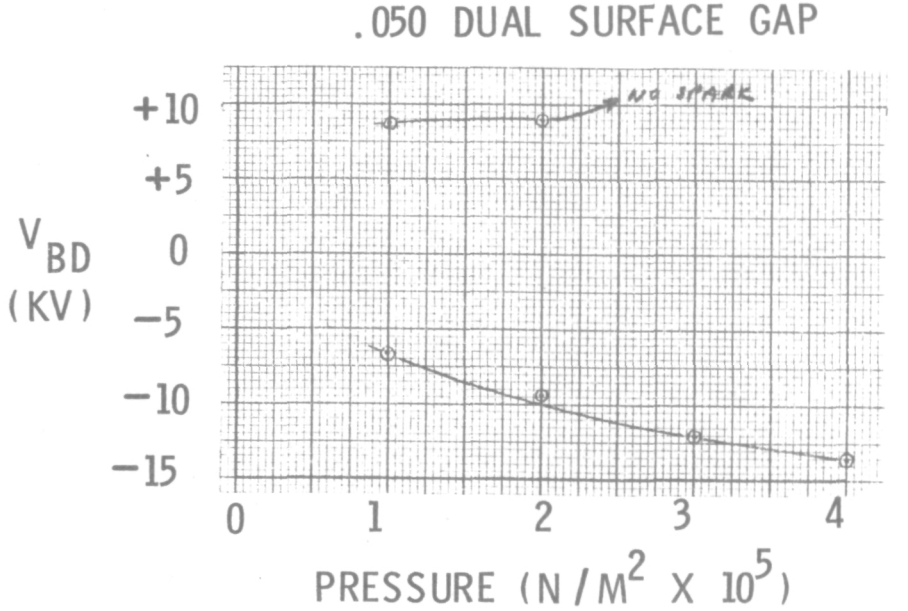
Figure 11

BREAKDOWN VOLTAGE VS. PRESSURE









TEMPERATURE LEGEND

△ — 144 K

⊙ — 297° K

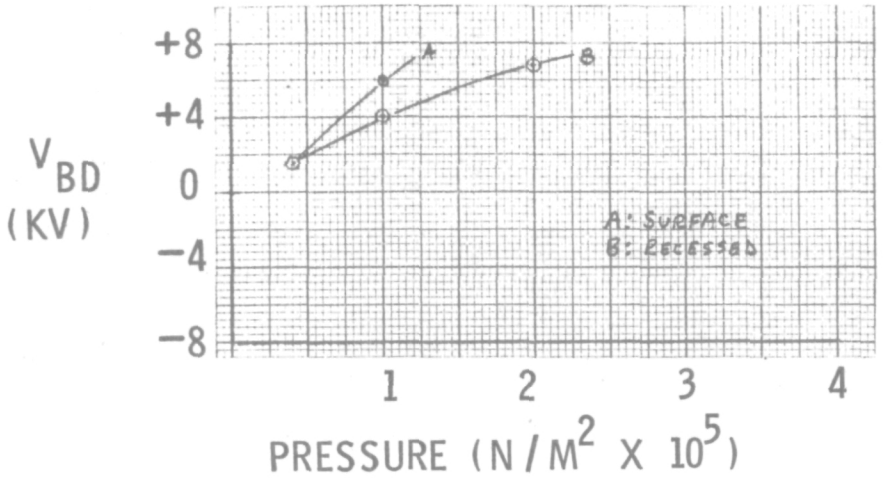
Figure 12

BREAKDOWN VOLTAGE VS. PRESSURE

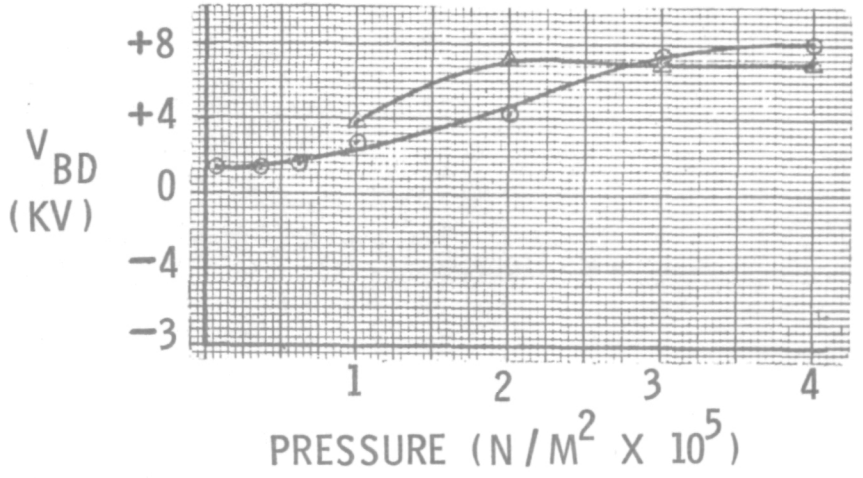
TEMPERATURE LEGEND

△ – 144° K
○ – 297° K

.050 SINGLE GAPS

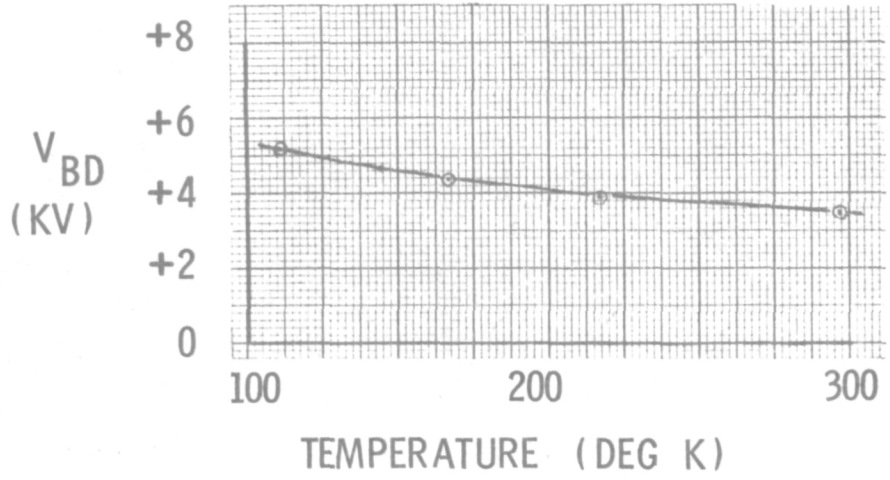


.050 RECESSED GAP (DOPED)

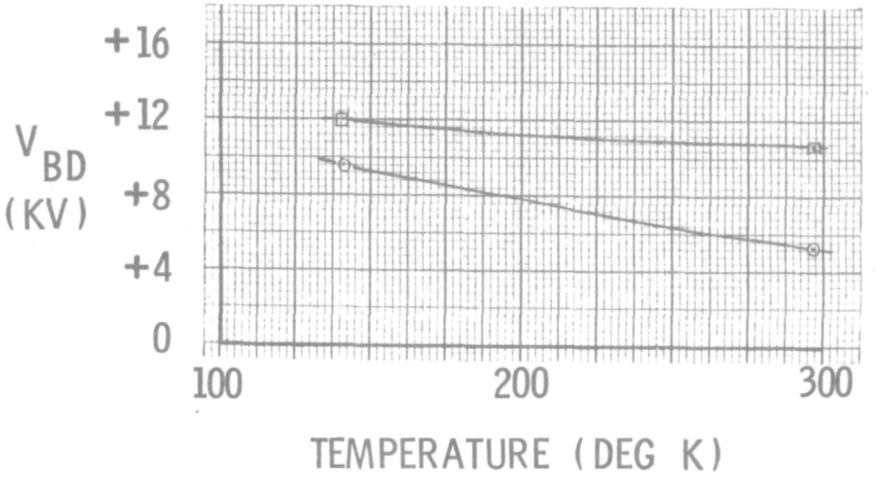


BREAKDOWN VOLTAGE VS. PRESSURE

.025 SURFACE GAP



.025 DUAL SURFACE GAP



PRESSURE LEGEND

⊡ 3×10^5 N/M^2

⊙ 1×10^5 N/M^2

Figure 13

BREAKDOWN VOLTAGE VS. TEMPERATURE

(doped) gap (Fig. 13). The platinum dopant effectivity limited the required breakdown voltage at about 8 kilovolts.

The non-uniform characteristics of the surface gap configurations can be considered to be analogous to point-to-plane gap characteristics. Studies of point-to-plane gaps (ref. "The Breakdown of Compressed Nitrogen in a Non-Uniform Field", I. Goldman and B. Wul) generally conclude that the effects of polarity on small gaps is small. It can be seen from the data that the differences due to polarity are fairly insignificant for all gaps tested. The predicted effect of polarity, however, indicates that a negative point electrode would require higher breakdown voltage than a positive point electrode. If the center electrode of the tested gaps is identified with the point electrode, in all cases the test data is inconsistent with the point-to-plane prediction. (However, the point-to-plane literature data was obtained with a 0.5-inch gap and it is possible that this characteristic is reversed for gaps that are an order of magnitude smaller.)

The reduced mobility of current carriers at low temperatures results in an increasing breakdown voltage with decreasing temperatures. This effect is minimized at elevated pressures. Figure 13 includes plots of breakdown voltage as a function of temperature. This trend can be seen in all of the preceding breakdown voltage vs pressure graphs that include multiple temperature plots with the exception of the 0.035-inch surface gap. The reversal of the breakdown voltage-temperature characteristics in this case is not of significant importance and was not explored further.

Spark Gap Sustaining Voltage

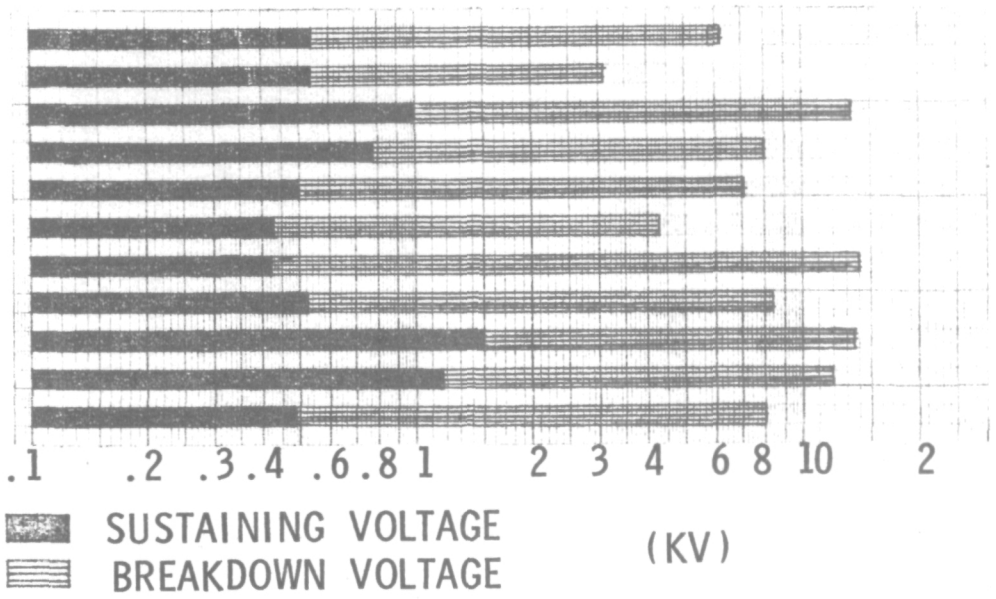
The sustaining voltage, the constant voltage level at which the spark gap stabilizes after breakdown, is a previously unexplored characteristic of inductively

powered spark gaps. The amplitude of the sustaining voltage affects the efficiency of the spark energy circuitry in that high voltage levels minimize the ampere-second product and thereby minimize copper losses in the transformer. Figure 14 illustrates the voltage characteristics of the various gap types tested. A logarithmic plot of average sustaining voltage and worst-case breakdown voltage for the various types reveals a pattern of decreasing sustaining voltage with increasing gap size and dual surface gap-sustaining voltages higher than single gap-sustaining voltages. The data becomes questionable for the 0.050-inch gap sustaining voltage in that few data points were taken. These measurements were of the quality shown in Fig. 16 discussed below. (A complete study of the 0.050-inch gap plugs was not made, their breakdown voltage requirements being in excess of 10 KV.) The plot of sustaining voltage as a percentage of breakdown voltage is presented in Fig. 14 for comparison purposes not easily obtainable from the logarithmic plot. Selecting 10 KV as a practical limit for the output of the spark exciter, the highest obtainable sustaining voltage is provided by the 0.025-inch dual recessed gap. This plug was chosen for ignition tests.

The volt-ampere characteristic of a gaseous discharge is illustrated in Fig. 15. The low energy levels delivered to the spark gap by the inductive energy system which is characteristically current limited, results in the dissipation of energy in the "glow discharge" region of the volt-ampere characteristics. The discharge of energy, in some cases, took place at lower current levels and in an apparent unstable region of the volt-ampere characteristics. This resulted in rapid voltage fluctuations after initial breakdown during which the energy was dissipated. Typical voltage waveforms for this type of operation are

GAP VOLTAGE CHARACTERISITICS

.025 SURFACE GAP
.025 RECESSED GAP
.025 DUAL SURFACE GAP
.025 DUAL RECESSED GAP
.035 SURFACE GAP
.035 RECESSED GAP
.050 SURFACE GAP
.050 RECESSED GAP
.050 DUAL SURFACE GAP
.050 DUAL RECESSED GAP
.050 RECESSED GAP (DOPED)



.025 SURFACE GAP
.025 RECESSED GAP
.025 DUAL SURFACE GAP
.025 DUAL RECESSED GAP
.035 SURFACE GAP
.035 RECESSED GAP
.050 SURFACE GAP
.050 RECESSED GAP
.050 DUAL SURFACE GAP
.050 DUAL RECESSED GAP
.050 RECESSED GAP (DOPED)

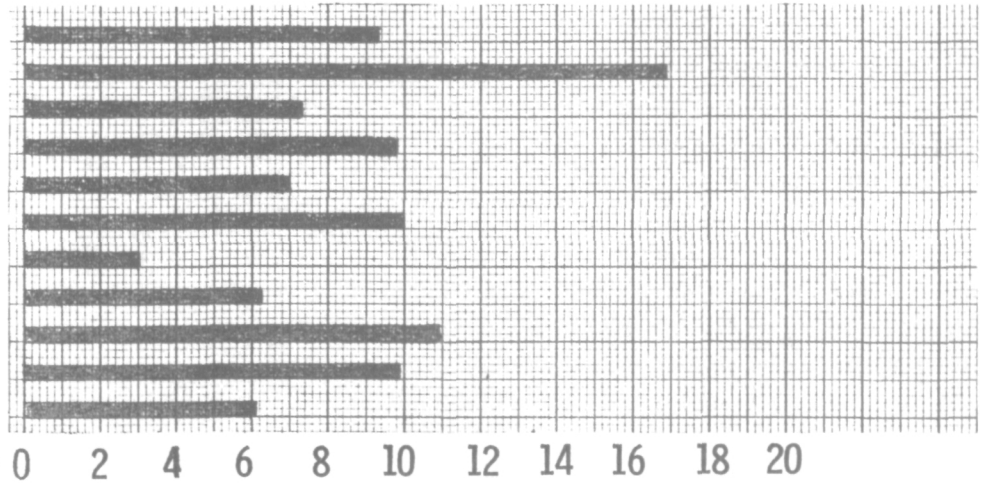


Figure 14

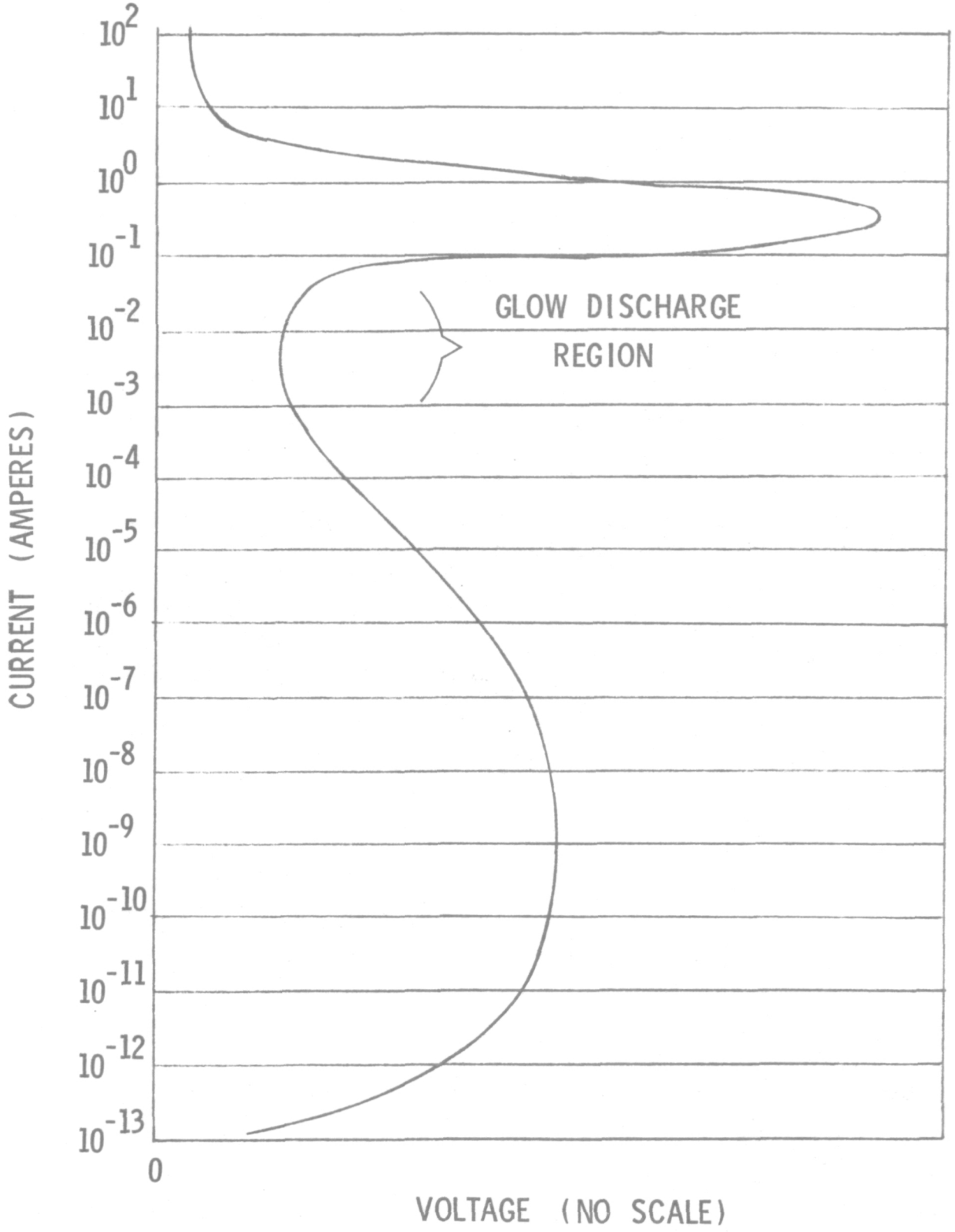

VOLT-AMPERE CHARACTERISTICS
OF A GASEOUS DISCHARGE
CURRENT (AMPERES)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
GLOW DISCHARGE
REGION
0
VOLTAGE (NO SCALE)

Figure 15

illustrated in Fig. 16. It is not known whether the average peak amplitude of this waveform is comparable to the typical D.C. level sustaining voltage obtained in other data. Spark energies capable of causing ignition are delivered at these levels but the data are not readily convertible to energy.

Repetitive Spark Effect

Results of tests on spark frequency effects on gap voltage-energy characteristics were inconclusive. The energy transfer-voltage step-up transformer in the variable energy power supply saturates as spark frequency is raised, resulting in a spark train of successively decreasing energy content. As a result, when setting a known low energy level developed from single spark testing, it was found that only the first few sparks contained sufficient current to establish a spark sustained discharge; subsequent circuit cycles did not cause spark gap discharge. Although continuous sparking was achieved by increasing the stored energy, the resultant higher initial energy cannot be meaningfully compared with single spark data. A further discussion on this characteristic of the variable energy unit is presented in a later section. On the successive sparks which did exhibit gap discharge, an insignificant change in gap breakdown voltage was noted.

Capacitive Energy Effects

Spark discharge tests employing an available capacitive energy system were not acceptable for meaningful comparison with the inductive energy tests. The discharge characteristic of the Rocketdyne variable capacitive energy console is oscillatory in nature and of such short duration (on the order of 10-20 μ seconds) that exacting measurements of breakdown voltage and gap current were not possible with available instrumentation. Available test time did not permit modification and requisition of more suitable instrumentation and the testing was terminated.

PHOTO # 63
.025 SURFACE GAP
1000 V/DIV
500 μS/DIV
(GAP VOLTAGE-POSITIVE POLARITY)

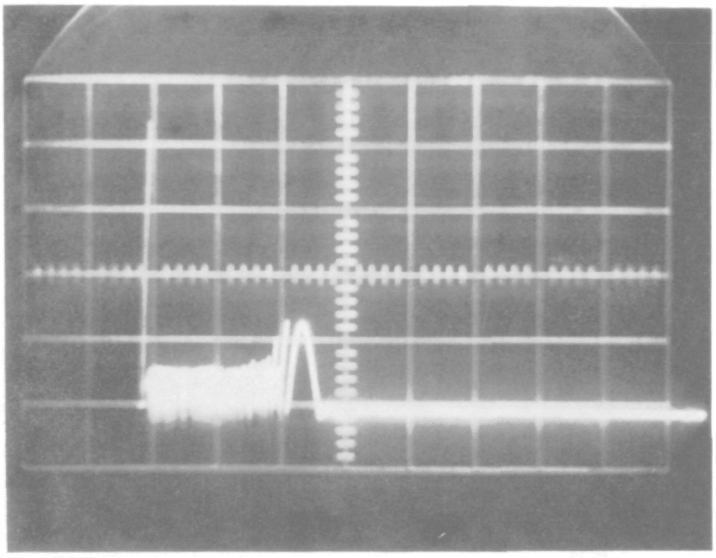
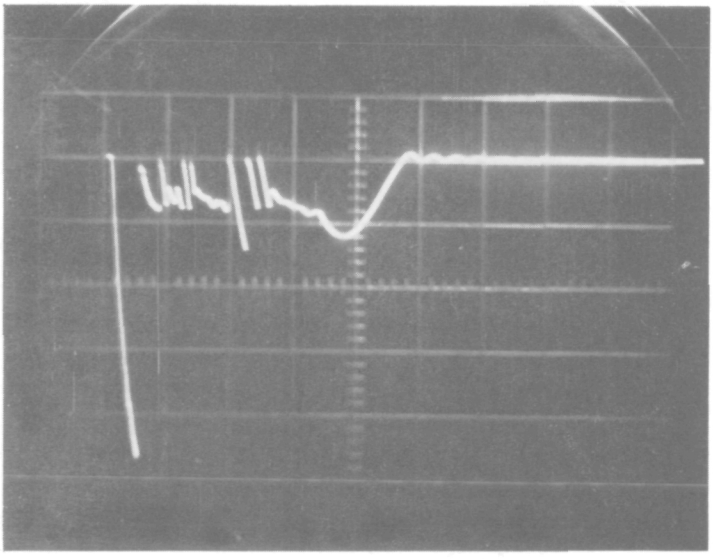


PHOTO # 253
.050 DUAL SURFACE
2000 V/DIV
200 μS/DIV
(GAP VOLTAGE-NEGATIVE POLARITY)



GAP VOLTAGE CHARACTERISTICS

Figure 16

Literature suggests that the faster rising voltage of a capacitive system would exhibit a higher gap breakdown point. Impulse dielectric values normally exceed D.C. and low frequency breakdown values. This disadvantage, coupled with parallel studies indicating greater circuit efficiencies and packaging advantagees are offered by an inductive system, justified termination of further capacitive energy evaluations at this time.

Spark Plasma Blossom

A photographic method for recording the blossoming effect of the spark discharge was developed prior to commencement of lab plug characterization tests. (See First Quartly Progress Report.) After selection of candidate plugs for hot fire evaluation (based on minimum voltage-maximum energy evaluation), attempts to record the plasma blossom were unsuccessful. The low energies and voltages achieved for satisfactory sparking result in the discharge being essentially contained within the boundary of the electrode/insulator cavities. Using the fastest available film, ASA10,000, no blossom extending beyond the leading edge of the plug face was recorded. Although good comparisons of blossom vs pressure had been obtained during the development phase, the energy levels at that time were an order of magnitude greater than the minimums determined by the plug lab tests. It is concluded that the low energy creates insufficient pressure in the plug electrode cavity to affect a significant plasma "torch".

Spark Plug Selection and Justification

The 0.025-inch dual recessed axial gap plug was selected for ignition tests as a result of the following observed characteristics:

1. The dual gap plugs operate at approximately twice the sustaining voltage of an equivalent single gap plug. Note that in Fig. 14 the

sustaining voltages for the recessed axial and the dual radial gaps are approximately 400 and 900 volts, respectively. The higher gap voltage minimizes circuit resistance energy losses and maximizes the exciter circuit efficiency.

2. The breakdown voltage of the dual recessed gap at 8 KV or less over the anticipated ASI operating range promises a smaller transformer ratio in the final exciter, which minimizes exciter input current for a given energy requirement.

3. The smaller gap requires less energy to guarantee that the spark will not quench. This is consistent with the Lewis and von Elbe findings on spark ignition energy and quenching distance. (Ref. NACA RM E57D24).

4. The plug tip may see temperature spikes as high as 5000° F. The recessed gap style will provide longer electrode life.

5. Although the J-2 spark plug, which has a significant test history at Rocketdyne, had approximately equal breakdown voltage characteristics, the lower sustaining voltage would affect overall efficiency. Also avoided by switching from the J-2 plug is the expensive platinum deposition process.

VARIABLE ENERGY EXCITER MODIFICATION

The variable induction stored energy exciter test console designed and built for spark plug laboratory characterization tests and igniter energy limit (Task II) exploration was further modified during this report period. The change was necessitated as a result of initial high pressure igniter tests at Los Angeles Division Thermodynamics Laboratory. In this early test series,

which required a spark rate of 200 sps, the combination of higher-than-anticipated pre-ignition pressure (160 psia -110 N/cm^2) and transformer saturation problems prevented reliable sparking with both the J-2 [0.050-inch (1.27 mm) doped recessed gap] and selected 0.025-inch (0.63 mm) dual recessed gap plugs.

To provide fuller understanding of the modification, a review of the variable exciter circuit and operation prior to the modification is presented. The schematic of the unit as employed during laboratory spark plug tests and low pressure igniter hot fire tests is shown in Fig. 17. Operation was as follows:

(a) The power supply section provides 15 VDC regulated power for the electronic network and rough 350 VDC for the energy storage network.

(b) The pulse rate oscillator provides variable frequency gating pulses for selection of spark rate.

(c) The firing pulse gate is a monostable multi-vibrator with Darlington output (Q_8, Q_9) which has a variable "on" time adjusted by R10 potentiometer. This circuit is very sensitive to electrical noise and hence was installed in a copper-lined box. Signal input leads (coded ①) were twisted and shielded. Power and output leads (coded ②) were shielded and entered the box circuit via in-line feed-through filters. The output of the firing pulse gate circuit drives the power switch Q_6.

(d) Energy is stored in inductor L_1 during the period of Q_6 operation. When Q_6 is switched "off", the inductor polarity reverses, voltage is applied across the primary of T_2 and the energy stored in the inductor is transferred to the high voltage output (connected to the

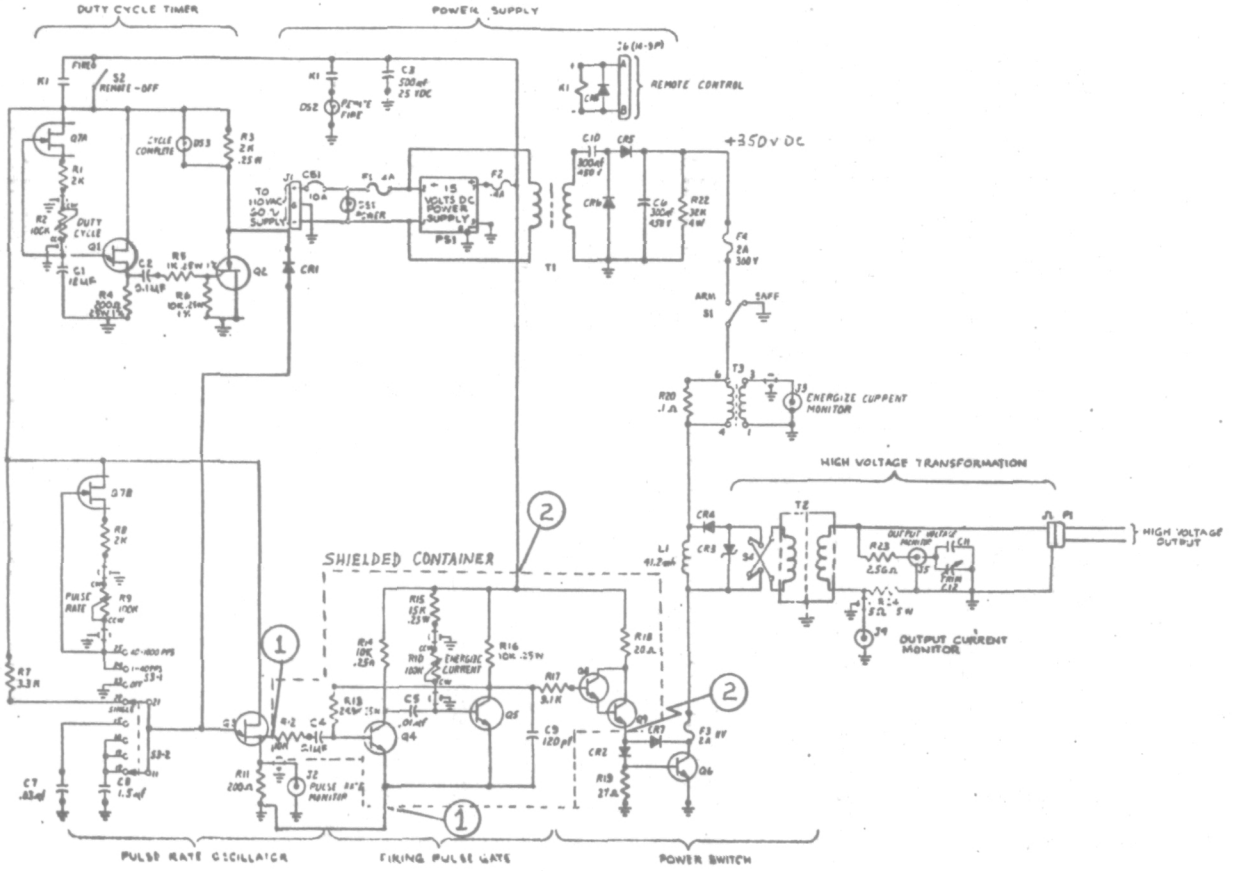


Figure 17

REVISIONS			
ZONE	LTR	DESCRIPTION	DATE
		1. MAY BE REWORKED 2. RECORD CHANGE 3. CANNOT BE REWORKED 4. NOW DROP PROGRESS 5. PARTS MADE OBS	
	A	REVISED CIRCUITRY	10-9-70
	B	REVISED CIRCUITRY	11-17-70

REF DES	PART NO	DESCRIPTION	MANUFACTURER OF MIL-SPEC
CR6	UT299	DIODE	UNITRODE
Q1	MU4893	TRANSISTOR	MOTOROLA
Q2	2N1770	TRANSISTOR	MOTOROLA
Q3	MU4893	TRANSISTOR	MOTOROLA
Q4	2N2222A	TRANSISTOR	TEXAS INSTR.
Q5	2N2222A	TRANSISTOR	TEXAS INSTR.
Q6	DTS808	TRANSISTOR	DELCO
Q7	SFC1037	TRANSISTOR	TEXAS INSTR.
Q8	2N2222A	TRANSISTOR	TEXAS INSTR.
Q9	2N2222A	TRANSISTOR	TEXAS INSTR.
T1	UTC-874	TRANSFORMER	UNITED TRANS
T2	F1659-2	TRANSFORMER	PACIFIC INSTR
T3	TF1RX12YY	TRANSFORMER	
S1	MS35058-23	SWITCH	
S2	MS35058-22	SWITCH	
S3	MS25082-2	SWITCH	
S4	MS35059-23	SWITCH	
R1	RN65H2001F	RESISTOR	MIL-R-55182
R2	AR100KL 25	RESISTOR	BECKMAN
R3	RN65H2001F	RESISTOR	MIL-R-55182
R4	RN65H2000F	RESISTOR	MIL-R-55182
R5	RN65H1001F	RESISTOR	MIL-R-55182
R6	RN65H1002F	RESISTOR	MIL-R-55182
R7	RN65H3301F	RESISTOR	MIL-R-55182
R8	RN65H2001F	RESISTOR	MIL-R-55182
R9	AR100KL 25	RESISTOR	BECKMAN
R10	AR100KL 25	RESISTOR	BECKMAN
R11	RN65H2000F	RESISTOR	MIL-R-55182
R12	RN65H1003F	RESISTOR	MIL-R-55182
R13	RN65H2492F	RESISTOR	MIL-R-55182
R14	RN65H1002F	RESISTOR	MIL-R-55182
R15	RN65H1502F	RESISTOR	MIL-R-55182
R16	RN65H1003F	RESISTOR	MIL-R-55182
R17	RN65H4701F	RESISTOR	MIL-R-55182
R18	RS-1/4-20 1%	RESISTOR	DALE
R19	RN65H2700F	RESISTOR	MIL-R-55182
R20	RS-1/4- .1 5%	RESISTOR	DALE
R22	CW-1-30K	RESISTOR	DALE
R23	2.5G	RESISTOR	VICTOREEN
R24	RW-5 5/- 1%	RESISTOR	DALE
L1	91.2mh	INDUCTOR	
J1		CONNECTOR	
J2	UG-290/U	CONNECTOR	
J3	UG-290/U	CONNECTOR	
J4	UG-299/U	CONNECTOR	
K1	C57BAP1N	RELAY	GUARDIAN
F1	HKP-MTH4	FUSE & HOLDER	BUSSMANN
F2	HKP-AGC 7/8	FUSE & HOLDER	BUSSMANN
F3	HKP-AGC7A	FUSE & HOLDER	BUSSMANN
F4	HKP-AGC2A	FUSE & HOLDER	BUSSMANN
DS1	95-0410-09-031	LIGHT	DIALIGHT
DS2	95-0410-09-031	LIGHT	DIALIGHT
DS3	95-0410-09-031	LIGHT	DIALIGHT
CR1	UT4005	DIODE	UNITRODE
CR2	1N3604	DIODE	MOTOROLA
CR3	UZ5230	ZENER DIODE	MOTOROLA
CR4	UT299	DIODE	UNITRODE
CR5	UT299	DIODE	UNITRODE
CR6	UT-299	DIODE	UNITRODE
CR7	1N3604	DIODE	MOTOROLA
CB1	MS25037	CIRCUIT BREAKER	
C1	126X9050R2	CAPACITOR	SPRAGUE
C2	104X9050A2	CAPACITOR	SPRAGUE
C3	500 ± 25VDC	CAPACITOR	SPRAGUE
C4	104X9050A2	CAPACITOR	SPRAGUE
C5	103X9050A2	CAPACITOR	SPRAGUE
C6	300-/ 450VDC	CAPACITOR	SPRAGUE
C7	303X9050A2	CAPACITOR	SPRAGUE
C8	156X9050A2	CAPACITOR	SPRAGUE
C9	120X9025A2	CAPACITOR	SPRAGUE
C10	300-/ 450VDC	CAPACITOR	SPRAGUE
C11	3000 pf	CAPACITOR	
C12	35pf VARIABLE	CAPACITOR	

NOTE: UNLESS OTHERWISE SPECIFIED

FINISH	NONE
MATERIAL	NONE
NEXT ASSY	

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH. MACH SURF REQUIRED. TOLERANCES ON ANGLES ± 0° 30' DECIMALS .00 ± .02 .000 ± .010 MACH SURF

DECIMAL	FRACTIONAL
.XX ± .02	± 1/64
.XXX ± .010	± 1/32
.XXXX ± .0050	± 1/16
.XXXXX ± .0025	± 1/8

DO NOT SCALE DRAWING

DRN	G. HESS
CHK	
ENGR	T. VAN
PROJ ENGR	
DESIGN AUTHORITY APVD	

Radiodyne Non-American Radiosol

SCHEMATIC - VARIABLE HI-VOLTAGE POWER SUPPLY

SIZE	CAGE NO	DRAWING NO
E	02602	MS3038-1-X

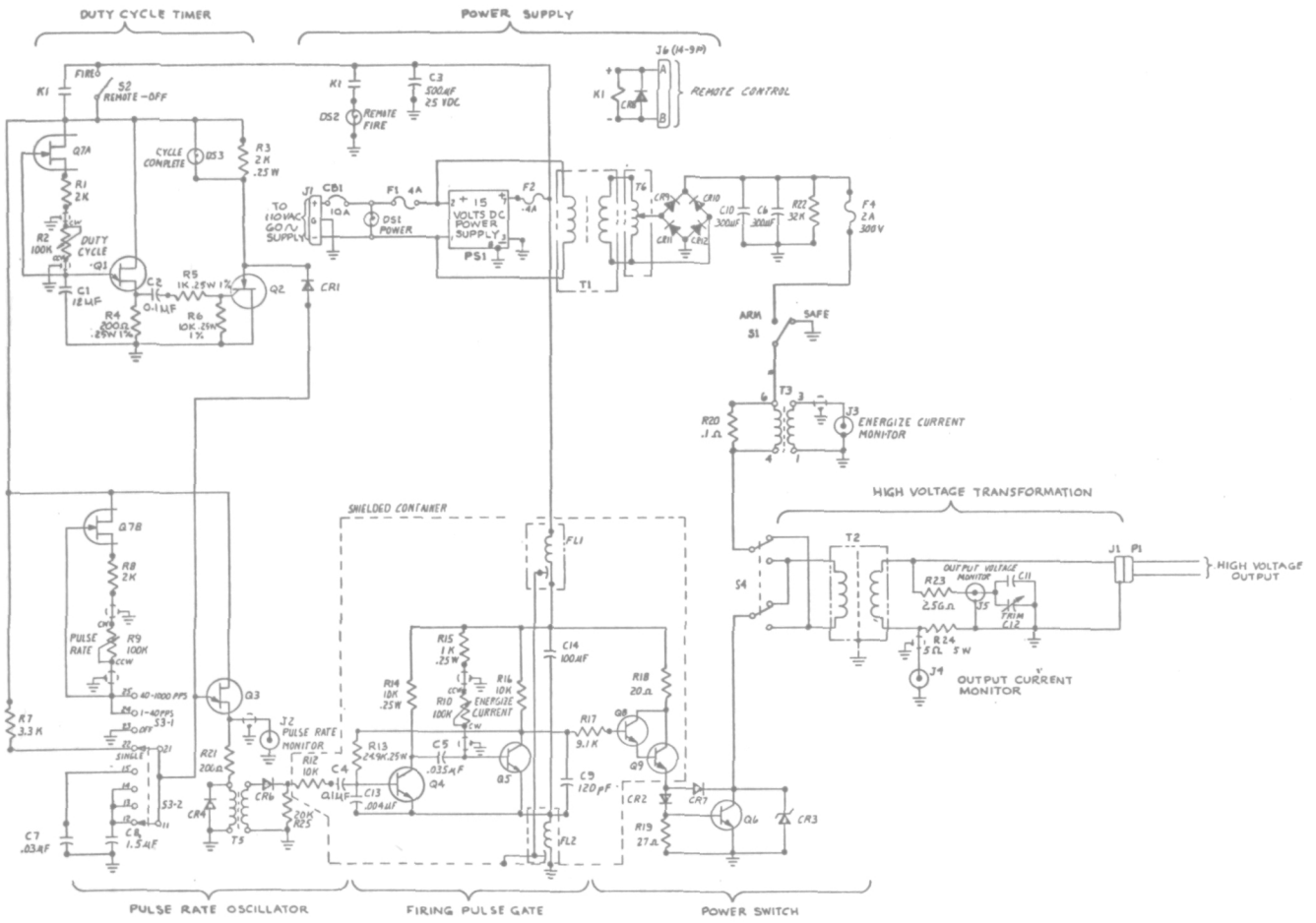
SCALE 1

the spark plug) by transformer action. The primary of T_2 has several taps for turns ratio selection, yielding potential output voltages of from 10 KV to 50 KV.

(e) In addition to instrumentation monitoring circuits provided, the unit contains a duty cycle timer which precluded inadvertent continuous operation of the variable energy unit and any connected spark plug. This circuit proved intermittent in operation due to noise sensitivity resetting the Q_2 silicon-controlled rectifier. During all laboratory testing and igniter firing tests, unit on-time was either manually controlled or automatically sequenced.

The difficulty in achieving consistent sparks which hampered initial high pressure igniter tests had not affected laboratory spark plug characterization nor low pressure igniter tests. Both of these latter test series operated with the spark plug media below 60 psia, and the unit energy output was adequate to create consistent sparking. The high pressure igniter initially operating at 160 psia required a voltage-current output exceeding the capability of the T_2 transformer. Investigation revealed that the transformer efficiency decayed to less than 10 percent at high voltage settings, and the transformer core would quickly saturate with repetitive sparks such that only the first few sparks of the train contained sufficient energy to create a spark discharge.

It was decided to convert the variable energy unit over to an output circuit more nearly simulating that planned for the integral spark igniter. The schematic of the revised unit is shown in Fig.18 and the significant operational changes are as follows:



REV	DESCRIPTION	DATE
	5. CANNOT BE REWORKED 6. NOW SHOP PRACTICE 5. PARTS MADE OK	
A	REVISED CIRCUITRY	10-9-70 Zeller
B	REVISED CIRCUITRY	11-17-70 Zeller
C	REVISED CIRCUITRY	1-20-71 Zeller

REF DES	PART NO.	DESCRIPTION	MANUFACTURER OR MIL-SPEC
C14	100μF	CAPACITOR	
C13	403X9050A2	CAPACITOR	SPRAGUE
T5	DI-T255	TRANSFORMER	UTC
T6		AUTOTRANS	
FL2		FILTER	
FL1		FILTER	
CR12	UT299	DIODE	UNITRODE
CR11	UT299	DIODE	UNITRODE
CR10	UT299	DIODE	UNITRODE
CR9	UT299	DIODE	UNITRODE
CR8	UT299	DIODE	UNITRODE
Q1	MU4893	TRANSISTOR	MOTOROLA
Q2	2N1770	TRANSISTOR	MOTOROLA
Q3	MU4893	TRANSISTOR	MOTOROLA
Q4	2N2222A	TRANSISTOR	TEXAS INSTR.
Q5	2N2222A	TRANSISTOR	TEXAS INSTR.
Q6	DTS804	TRANSISTOR	DELCO
Q7	SPC1037	TRANSISTOR	TEXAS INSTR.
Q8	2N2222A	TRANSISTOR	TEXAS INSTR.
Q9	2N2222A	TRANSISTOR	TEXAS INSTR.
T1	UTC-R14	TRANSFORMER	UNITED TRANS
T2	F1659-2	TRANSFORMER	PACIFIC INSTR
T3	DI-T255	TRANSFORMER	UTC
S1	MS3505B-23	SWITCH	
S2	MS3505B-22	SWITCH	
S3	MS25002-2	SWITCH	
S4	MS3505G-23	SWITCH	
R1	RN65H2001F	RESISTOR	MIL-R-55182
R2	AR100KL 2%	RESISTOR	BECKMAN
R3	RN65H2001F	RESISTOR	MIL-R-55182
R4	RN65H2000F	RESISTOR	MIL-R-55182
R5	RN65H1001F	RESISTOR	MIL-R-55182
R6	RN65H1002F	RESISTOR	MIL-R-55182
R7	RN65H3301F	RESISTOR	MIL-R-55182
R8	RN65H2001F	RESISTOR	MIL-R-55182
R9	AR100KL 2%	RESISTOR	BECKMAN
R10	AR100KL 2%	RESISTOR	BECKMAN
R11	RN65H2000F	RESISTOR	MIL-R-55182
R12	RN65H1002F	RESISTOR	MIL-R-55182
R13	RN65H2492F	RESISTOR	MIL-R-55182
R14	RN65H1002F	RESISTOR	MIL-R-55182
R15	RN65H1002F	RESISTOR	MIL-R-55182
R16	RN65H1002F	RESISTOR	MIL-R-55182
R17	RN65H9102F	RESISTOR	MIL-R-55182
R18	RS-1/4-20 1%	RESISTOR	DALE
R19	RN65H27R0F	RESISTOR	MIL-R-55182
R20	RS-1/4- 1 5%	RESISTOR	DALE
R21	RN65H2000F	RESISTOR	MIL-R-55182
R22	CW-5-32K	RESISTOR	DALE
R23	2.5G	RESISTOR	VICTOREEN
R24	RH-5 5Ω 1%	RESISTOR	DALE
R25	RN65H2002F	RESISTOR	MIL-R-55182
J1		CONNECTOR	
J2	UG-290/U	CONNECTOR	
J3	UG-290/U	CONNECTOR	
J4	UG-290/U	CONNECTOR	
K1	C526AP2N	RELAY	GUARDIAN
F1	HKP-MTH4	FUSE & HOLDER	BUSSMANN
F2	HKP-AGC 1/8	FUSE & HOLDER	BUSSMANN
F4	HKP-AGC7A	FUSE & HOLDER	BUSSMANN
DS1	95-0410-09-031	LIGHT	DIALIGHT
DS2	95-0410-09-031	LIGHT	DIALIGHT
DS3	95-0410-09-031	LIGHT	DIALIGHT
CR1	UT4005	DIODE	UNITRODE
CR2	IN3869	DIODE	MOTOROLA
CR3	UZ5230	ZENER DIODE	MOTOROLA
CR4	UT299	DIODE	UNITRODE
CR5	UT299	DIODE	UNITRODE
CR6	UT-299	DIODE	UNITRODE
CR7	IN3869	DIODE	MOTOROLA
CB1	MS25017	CIRCUIT BREAKER	
C1	126X9050R2	CAPACITOR	SPRAGUE
C2	104X9050A2	CAPACITOR	SPRAGUE
C3	500 f 25V DC	CAPACITOR	SPRAGUE
C4	104X9050A2	CAPACITOR	SPRAGUE
C5	353X9050A2	CAPACITOR	SPRAGUE
C6	300 f 450V DC	CAPACITOR	SPRAGUE
C7	303X9050A2	CAPACITOR	SPRAGUE
C8	156X9050A2	CAPACITOR	SPRAGUE
C9	1200X9050A2	CAPACITOR	SPRAGUE
C10	300 f 450V DC	CAPACITOR	SPRAGUE
C11	5000 pf	CAPACITOR	
C12	250pf VARIABLE	CAPACITOR	

HEAT TREAT	NONE	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH. 125 MACH. SURF. ROUGHNESS	DRN G. HUIES DATE
FINISH	NONE	TOLERANCES ON ANGLES ± 30' DECIMALS .XX ± .03 .XXX ± .010 HOLES NOTED "DRILL" OVER THRU TOLERANCE .0000 .0400 +.0015 −.0010 .0401 .1300 +.0025 −.0010 .1301 .2250 +.0030 −.0010 .2251 .3500 +.0040 −.0010 .3501 .7500 +.0070 −.0010 .7501 1.0000 +.0090 −.0010 1.0001 2.0000 +.0120 −.0010	CHK DATE
MATL	NOTED	DO NOT SCALE PRINT	DSGN DATE 1-20-71 MATL STRUCT DESIGN ACTIVITY APVD DATE

Rocketdyne — North American Rockwell — Canoga Park, California — McGregor, Texas

SCHEMATIC - VARIABLE HI-VOLTAGE POWER SUPPLY

SIZE	CAGE IDENT NO.	DRAWING NO.
E	02602	RS002496X

SCALE FULL SIZE SHEET 1

NOTE: UNLESS OTHERWISE SPECIFIED

(a) A new transformer, T_2, is used directly as the energy storage-transfer device. It provides a fixed 42:1 turns ratio, having a capability of 25 KV maximum output. The core, primary winding, and charging time were designed to provide a maximum stored energy of 320 millijoules.

(b) The 350 VDC power supply was replaced with a Variac (T_6) and full-wave bridge to provide variable voltage direct current. The variable energy exciter unit was nominally sized for a 60-volt supply; however, the unit was energy-calibrated at 25, 60, 90, and 125 VDC. At the 60-volt setting, stored energy in the transformer core is variable from 0.1 to 302 millijoules.

(c) Improved filtering and an input isolation network were added to the firing pulse gate circuit to further improve the circuit's noise sensitivity. The combination of the feed-through filters FL_1 and FL_2, along with capacitor C_{14} effectively eliminated all power supply conducted noise. Transformer T_5, steering diode CR_4, and filter C_{13} effectively decoupled and damped all transients on the circuit input. The operation of the circuit was otherwise unchanged, still providing a variable duration gating signal to the power switch, Q_6.

(d) The energy storage-transfer cycle is identical to that being designed for the prototype integral spark igniter (discussed in a later section of this report). During the "on" period of Q_6, current increases in the T_2 primary proportional to the applied voltage and effective transformer inductance. The resultant magnetic field stores energy in the transformer core. When Q_6 is switched off, the established

field causes the transformer to reverse polarities and to increase the winding voltages until spark plug breakdown occurs. When the spark gap conducts, the energy stored in the field is transferred to the gap.

(e) The remaining functional sections of the unit operate as before.

In addition to providing an energy source capable of operating the selected spark plug under very high pressure conditions, the modified unit served as a valuable proving ground for efficient transformer design. One of the keys to the low power, low energy integral spark igniter design, which has a goal of greater than 50 percent efficiency, is its transformer. Recognizing that the new T_2 transformer was sized for a maximum energy an order of magnitude greater than the integral unit design goal (300 to < 30 mj), an efficiency of 80 percent was realized at the high energy setting.

Additional Evaluation of Variable Energy Unit

As discussed more fully in the test data section (Task II high pressure igniter), the voltage developed on the output of the variable energy unit during the storage cycle caused intermittent breakdown of the spark gap in a mode which could not be correlated with laboratory voltage-current measurements. At the conclusion of the igniter hot-fire testing, therefore, two special sets of measurements were taken of spark energy with the selected spark plug operating in a transient pressure regime of vacuum [0.2 psia (.013 N/cm^2)] to high pressure hydrogen.

In the first measurement series, oscilloscope records were made of spark voltage and current with the electrical system connections identical to that extant during the hot-fire testing. Data analysis revealed that:

(a) The apparent breakdown voltage in hydrogen was approximately one-half that experienced in GN_2,

(b) When the breakdown occurred on the charging half of the energy storage-transfer cycle, the unit load (cables and spark plug) behaved somewhat like a capacitor, and

(c) When the load resembled a capacitor, there was no evidence of normal voltage discontinuities associated with an arc discharge.

These observations, coupled with the test-to-test and spark-to-spark inconsistencies prevalent in the data, led to the conclusion that very few spark discharges had actually occurred during the hot-fire tests at low energy settings (at high-stored energies, a more consistent spark discharge was evidenced). Due to the quality of this series of measurements, a reasonable estimate of spark energy could not be made. An additional test series was therefore conducted.

In this final series, a 5 KV breakdown diode was installed in the unit high voltage output circuit to preclude dissipation of energy during the energy-storage cycle. Using the selected plug and varying the gas media at the plug tip, a consistent set of spark data were generated from which spark energy could be readily defined. A summary of this data is tabulated in Table 2. Also tabulated is a series of measurements taken by close-coupling the spark plug to the variable energy unit to determine the losses attributable to the long high-tension leads employed during the hot-fire testing.

It is apparent that less energy is dissipated in hydrogen than in nitrogen, and both increasing pressure and decreasing temperature further decrease the delivered energy. A literature search has divulged little information regarding the dielectric properties of hydrogen under high pressure, low temperature

DUAL RECESSED GAP PLUG ENERGY MADE VARYING CONDITIONS, MILLIJOULES

TABLE 2

Stored Energy, mJ	Gas Media	GN_2	GH_2	GH_2	GH_2	GH_2	GH_2	GH_2	GH_2	* Air
	Temperature °K	294	111 - 294 **	294	294	194	194	111	111	294
	Pressure $N/m^2 \times 10^5$	1.01	0.1	6.89	13.79	6.89	12.79	6.895	12.79	1.01
133		37	55	36	27	25	24	22	16	64
96		27	40	25	18.5	17.5	16.5	14	10	46
81		23	33	20	15	14	13	11	7.5	40
66		18	27	16	11.5	11	10	8.2	5.8	32
47		10	16	8.5	6.2	6	5	4.5	2.8	19
27		4.5	9	4	2.7	2.5	2	1.7	1.0	8.5
12		1.0	2.5	0.9	-	-	-	-	-	1.6
2		0.1	-	-	-	-	-	-	-	0.1

* Data taken with close-coupled spark plug, no high voltage cables.

** Spark energy data over the noted temperature range were nearly equal. Average values are tabulated.

conditions. It can be theorized that as the hydrogen becomes less conductive as temperature decreases (as witnessed by generally higher breakdown and sustaining voltages) the higher effective impedance of the gap results in less average current and higher quenching current. The net volt-ampere time integral has less content. A similar analogy prevails for increasing pressure, although the gap voltage characteristic during arcing assumed a high amplitude, high frequency oscillatory nature difficult to analyze for a "true" sustaining voltage as experienced in GN_2 tests.

Of considerable significance is the comparison of the first and last data columns in Table 2. The energy losses in the high tension cables (the difference between columns are approximately equal to the energy delivered to the plug through the cable. This fact again supports design belief in the expected high efficiency of the integral spark igniter.

INTEGRATED PLUG/EXCITER

Mechanical and functional design of the prototype integral spark igniter proceeded during this report period in parallel with input data from Task II igniter testing. The dual recessed gap electrode configuration selected from laboratory characterization tests of several types was redesigned from the "half-plug" configuration to decrease size and provide a suitable interface for the sealed electronics package. Procurement of the modified plug was initiated with Alberox Corporation. Circuit design and analysis for the exciter electronics was conducted on several candidate circuits, and initial breadboard testing was performed on a blocking oscillator circuit selected as promising high efficiency and simplicity. With all other electronic components on hand, the energy storage/transfer transformer is undergoing final design for procurement at the beginning of the next contract period. Completion of the integrated limit is targeted for completion the first week of March 1971.

Design Status

The assembly layout of the prototype integral spark igniter is included as Fig. 19. Detailing of the spark plug portion was completed and fabrication of this long-lead item has commenced. Detailing of the electronic module was enabled by construction of a working breadboard circuit. The components are readily packaged into a cylindrical module 0.75 inch (1.90 cm) thick and less than 2 inches (5.08 cm) in diameter. The electronics module, however, does not fix the diameter of the housing; the special energy storage transformer does. Before committing the simple sheet metal case assembly to fabrication, final testing of a transformer properly sized for the design point energy and output voltage will be accomplished.

Circuit design of the spark igniter has been essentially completed. The preliminary schematic is shown in Fig. 20, and consists of three basic elements: (1) a spark frequency relaxation oscillator (Q_3 circuit), (2) a constant current regulator (Q_1 circuit), and (3) a blocking oscillator power/energy stage (Q_2-T_1 circuit). Using available transformer materials, this circuit has been operated in a breadboard setup; however, the present breadboard stored energy (limited by the availability of a transformer core) is slightly less than the integral unit design point. The breadboard has an output of 8 millijoules at 200 sparks/second (design point 10 mj), while drawing approximately 120 mA constant current. Output voltage is sized for 10 KV. The laboratory-wound C-core transformer efficiency is 65 percent with a total circuit efficiency of 45 percent. It is expected that a production-wound toroidal core will approach 75 to 85 percent efficiency, and provided circuit adjustments remain within anticipated limits, a total system efficiency of 60 percent is predictable. If this is achieved, the design goal ($>$ 60 percent efficiency energy storage/energy delivered) will be exceeded.

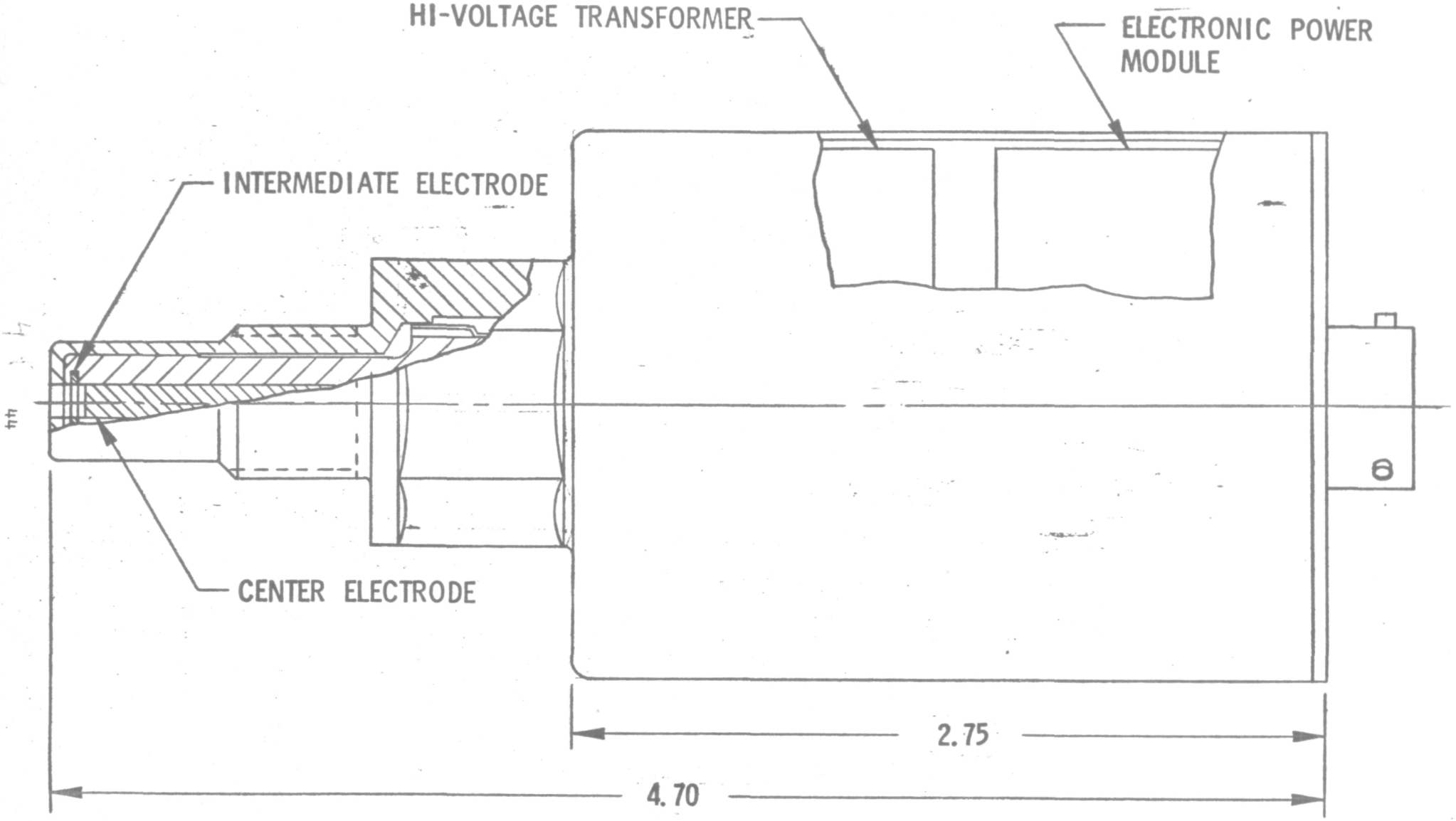
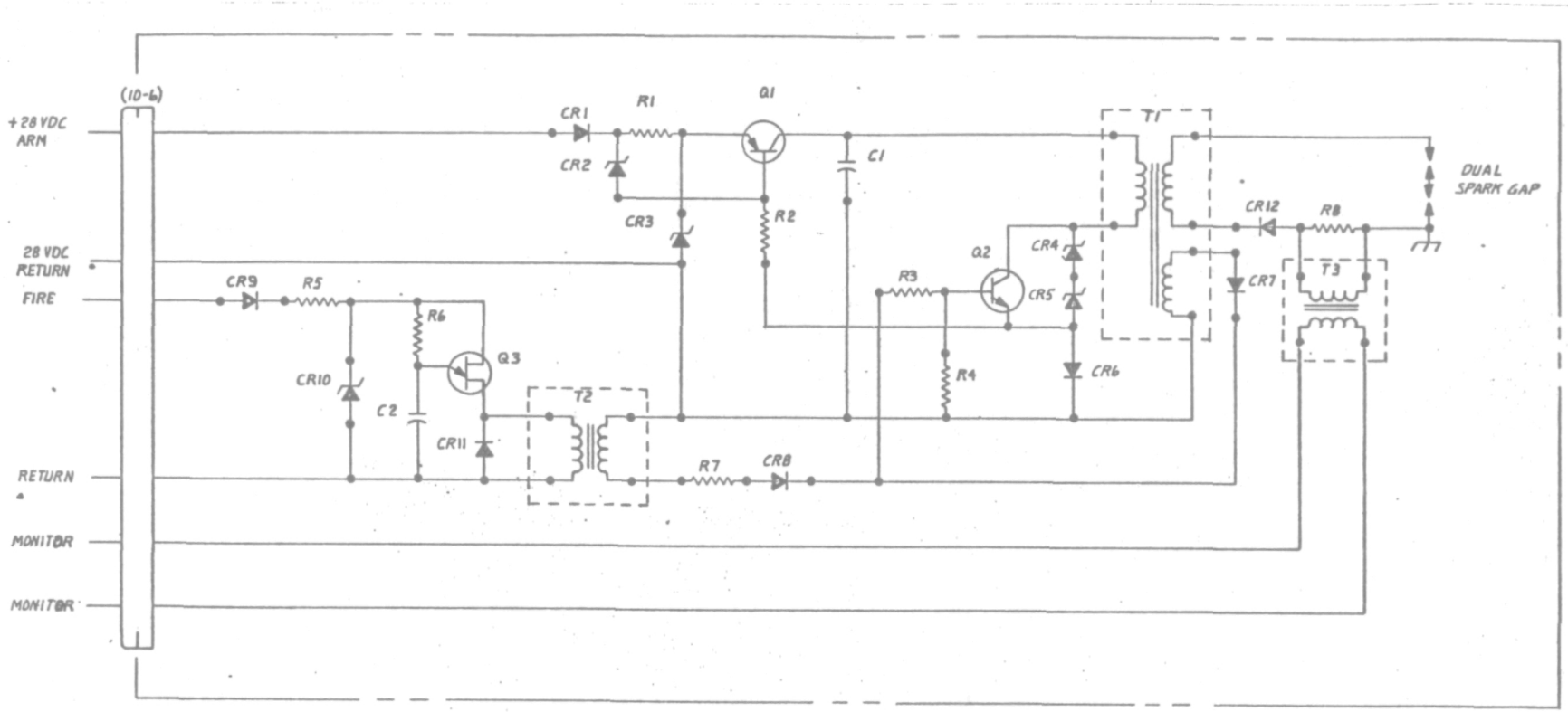


Fig 19

APS SPARK IGNITER

Figure 19



PRELIMINARY SCHEMATIC
PROTOTYPE SPARK IGNITER

Figure 20

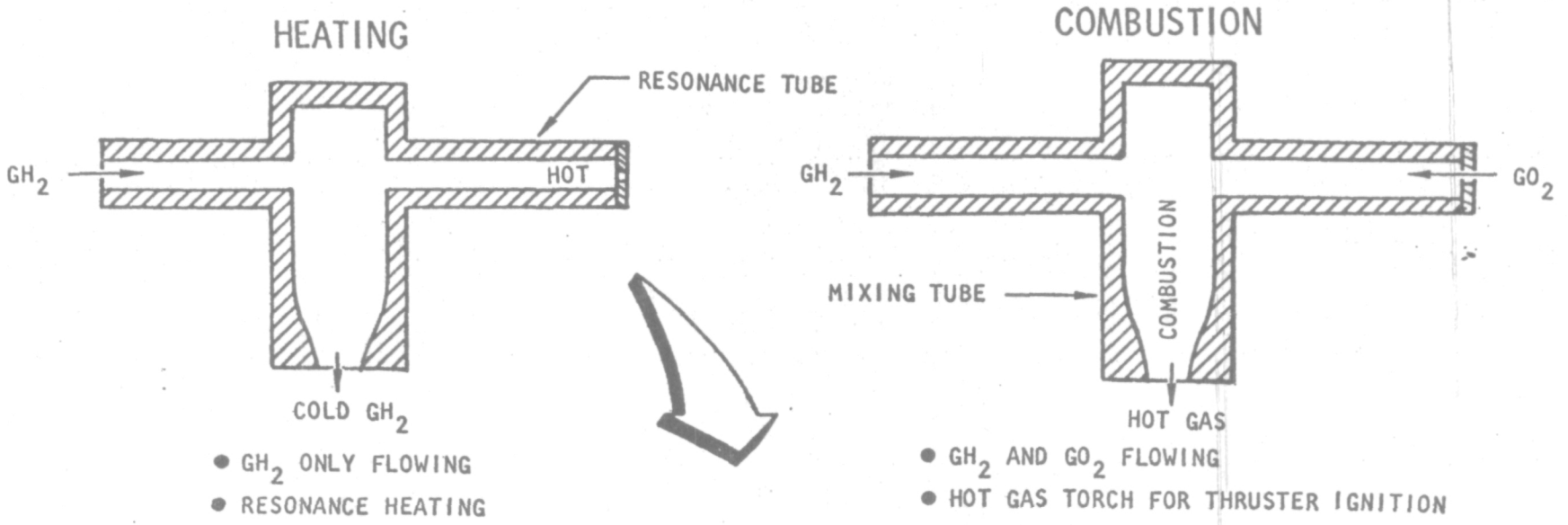
AUTO IGNITER

During this report period, the major efforts were devoted to (1) the analysis of the test data obtained during the resonance igniter phenomena investigations, wherein the test hardware was of variable geometry, (2) the design and fabrication of a fixed geometry resonance igniter suitable for integration into the existing Rocketdyne SS/APS thrust chamber injector, and (3) planning of a test program for the latter igniter.

The basic operating principles of the auto igniter are: (1) heating of hydrogen by setting up a resonance condition in a closed ended tube and (2) introduction of oxidizer and subsequent combustion as the heated hydrogen is mixed with oxygen while the gases are being forced out of the resonance tube by the oxygen (see Fig. 21). The resonance heating in the closed ended tube is achieved by repetitive compression created by the shock structure of the under-expanded hydrogen as it "jumps" the gap between the sonic nozzle and the inlet of the resonance tube. During a Rocketdyne-sponsored IR&D task, temperatures as high as 2910 R (1620 K) were achieved by resonance heating using helium at a total pressure of approximately 1000 psia (6.895×10^6 N/m^2) (see Fig. 21. For the current investigation, temperatures above 2960 R (1640 K) were measured using hydrogen at a total pressure of approximately 375 psia (2.58×10^6 N/m^2).

The following paragraphs will include discussions of the phenomena test data analysis, descriptions of the fixed geometry resonance igniter design and fabrication (as performed under the Task I effort of the program).

O_2/H_2 AUTO IGNITER (RESONANCE)



- GH_2 ONLY FLOWING
- RESONANCE HEATING

- GH_2 AND GO_2 FLOWING
- HOT GAS TORCH FOR THRUSTER IGNITION

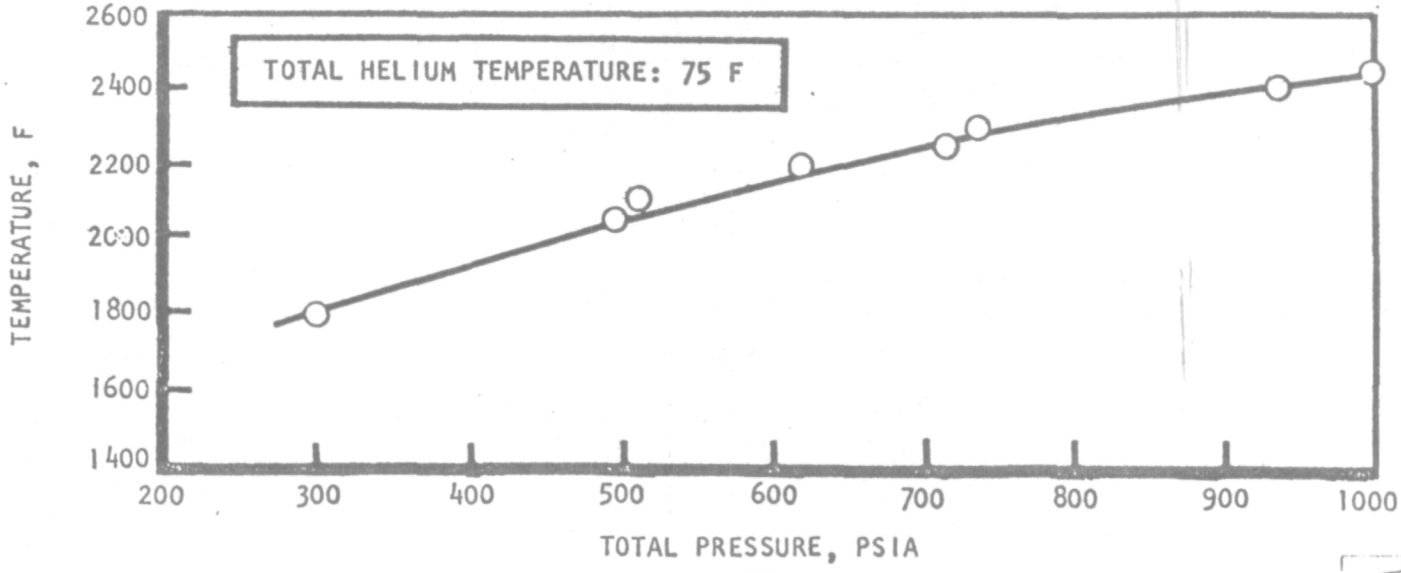


Figure 21

PHENOMENA TEST DATA ANALYSIS

During the auto-igniter phenomena investigation, 442 tests were conducted. Table 3 indicates the configurations tested and the pertinent variables, and also gives a brief summary of the results. More detailed description of the test will be given below.

Geometrical Characterization. For a given hydrogen flowrate, there are three basic geometrical parameters which determine the effectiveness of the resonance igniter in terms of achieving maximum hydrogen temperature in a minimum time. The three geometrical parameters are: (1) the resonance tube configuration, (2) the gap distance between the hydrogen nozzle exit plane and the inlet to the resonance tube, and (3) the restriction area at the exit of the mixing chamber. From previous test programs and from the test results obtained in the current program, it can be shown that the three geometrical parameters are closely coupled, i.e., modifying one parameter will affect the other two to achieve an "optimum" igniter configuration.

Resonance Tube. Past experimental investigations have shown that for a given gap distance and jet pressure ratio, there are a number of discrete ratios of resonance tube length to inlet diameter (L/D) which will lead to peak gas temperatures. In addition, it has also been demonstrated that for a fixed L/D ratio, a stepped-tapered tube provides for higher gas temperatures than can be reached with either straight or smoothly tapered resonance tubes. Furthermore, it has also been found that there exists an optimum ratio between the resonance tube inlet diameter and the jet throat diameter (D/d). Since the resonance tube geometry by itself incorporates several variables (L/D, D/d, angle of taper, number of steps), all of which require optimization to achieve maximum

TABLE 3

AUTO-IGNITION BASIC PHENOMENA TEST RESULTS

RESONANCE IGNITER TEST MATRIX

TEST	CONFIGURATION	VARIABLES	RESULTS
1-56	STEPPED/TAPERED TUBE CONF. I (H_2 AMBIENT)	GAP DISTANCE, RESTRICTION AREA	OPTIMIZATION OF GAP DISTANCE AND RESTRICTION AREA
57-124	STEPPED/TAPERED TUBE CONF. II (H_2 AMBIENT)	GAP DISTANCE, RESTRICTION AREA, THERMOCOUPLE TYPE	OPTIMIZATION OF GAP DISTANCE AND RESTRICTION AREA
125-139	STEPPED/TAPERED TUBE CONF. II (H_2 AMBIENT)- OPTIMUM GAP	HEAT EXCHANGER IN SYSTEM	EFFECT OF HEAT EXCHANGER IN SYSTEM ON RESONANCE TEMPERATURE-TIME RELATION
140-180	STEPPED/TAPERED TUBE CONF. II - OPTIMUM GAP	H_2 TEMPERATURE	EFFECT OF H_2 TEMPERATURE ON RESONANCE TEMPERATURE-TIME RELATION
180-242	STEPPED/TAPERED TUBE CONF. I (H_2 AMBIENT)- OPTIMUM GEOMETRY	SMALL VOLUMES AT END OF RESONANCE TUBE	EFFECT OF ADDITIONAL CAVITIES AT END OF RESONANCE TUBE
243-284	STEPPED/TAPERED TUBE CONF. I - OPTIMUM GEOMETRY	H_2 AND O_2 FLOWRATES (H_2 AND O_2 AT AMBIENT)	IGNITION/COMBUSTION OVER A RANGE OF MIXTURE RATIOS IGNITION DELAY

TABLE 3 (CONT'D)

AUTO-IGNITION BASIC PHENOMENA TEST RESULTS

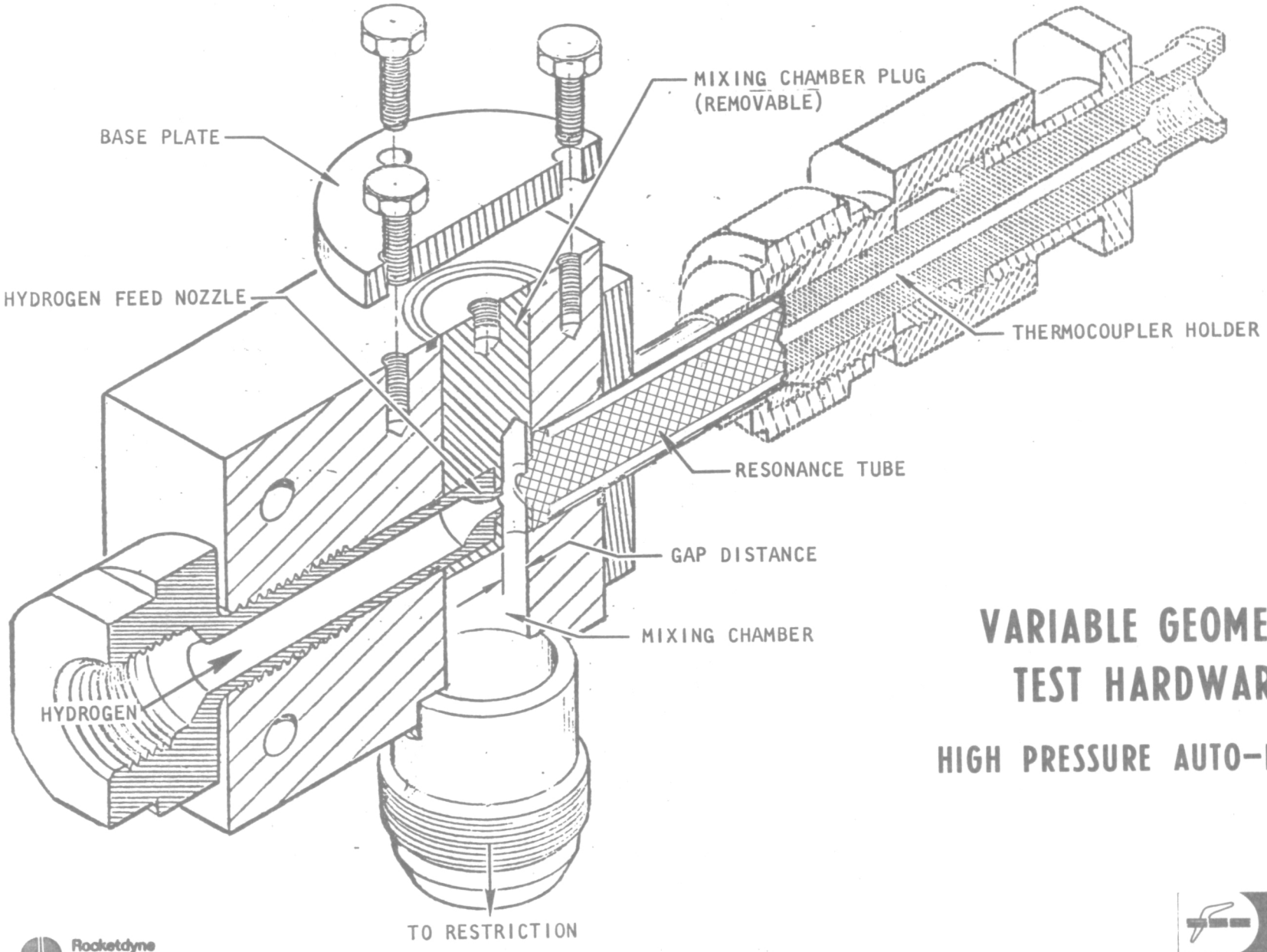
RESONANCE IGNITER TEST MATRIX

TEST	CONFIGURATION	VARIABLES	RESULTS
285-316	STEPPED/TAPERED TUBE CONF. I - OPTIMUM GEOMETRY	H_2 AND O_2 TEMPERATURE AND FLOWRATES	IGNITION/COMBUSTION OVER RANGE OF MIXTURE RATIOS IGNITION DELAY, VALVE SEQUENCING
317-349	STEPPED/TAPERED TUBE CONF. I - OPTIMUM GEOMETRY (H_2 AMBIENT)	H_2 AND O_2 PRESSURE AND FLOWRATES	IGNITION/COMBUSTION OVER RANGE OF MIXTURE RATIOS IGNITION DELAY, VALVE SEQUENCING
350-359	STEPPED/TAPERED TUBE CONF. I - OPTIMUM GEOMETRY (H_2 AMBIENT)	H_2 PRESSURE	EFFECT OF H_2 PRESSURE ON RESONANCE TEMPERATURE
360-442	STEPPED/TAPERED TUBE CONF. III (H_2 AMBIENT)	GAP DISTANCE, RESTRICTION AREA, THERMOCOUPLE TYPE	OPTIMIZATION OF GAP DISTANCE AND RESTRICTION AREA FOR LOW-PRESSURE RESONANCE IGNITER

temperature in minimum time, it was decided to investigate the performance of two resonance tube geometries which had been previously optimized by other investigators. The two geometries will be referred to as configurations I and II. The resonance tube configurations were made out of quartz to reduce the heat transfer loss.

Gap Distance and Restriction Area. With one of the resonance tube configurations placed in a variable geometry test hardware (see Fig.22), the restriction area was varied by means of an Annin valve, while keeping a fixed gap distance. For a given restriction area setting, the hydrogen gas temperature was measured by means of a high response thermocouple located at the end of the resonance tube. This procedure was repeated for different gap distances. All of the geometry optimization tests were conducted with hydrogen at ambient temperature.

With configuration I resonance tube, the ratio of the gap distance to nozzle throat diameter (G/d) was incrementally varied between 1.34 and 3.775, while for each gap setting the ratio of hydrogen injection pressure to mixing chamber pressure (P_T/P_{MC}) was varied between 3.9 and 5.15. Figure 23 shows the time required for the hydrogen to read 1460 R (temperature criterion to cause O_2/H_2 ignition) as a function of the gap to nozzle diameter ratio. All points indicated on Fig.23 were taken at optimum restruction area settings. The optimum (P_T/P_{MC}) ratio (or equivalent optimum restriction area) is shown on Fig. 24 as a function of G/d. Figure 23 indicates that for configuration I the time (22 msec) to reach 1460 R is achieved with a G/d of 3.426, and Fig. 24 shows that the corresponding P_T/P_{MC} ratio is 5.14.



VARIABLE GEOMETRY TEST HARDWARE

HIGH PRESSURE AUTO-IGNITER

Rocketdyne
North American Rockwell

space shuttle engine
AUXILIARY PROPULSION SYSTEM

Figure 22

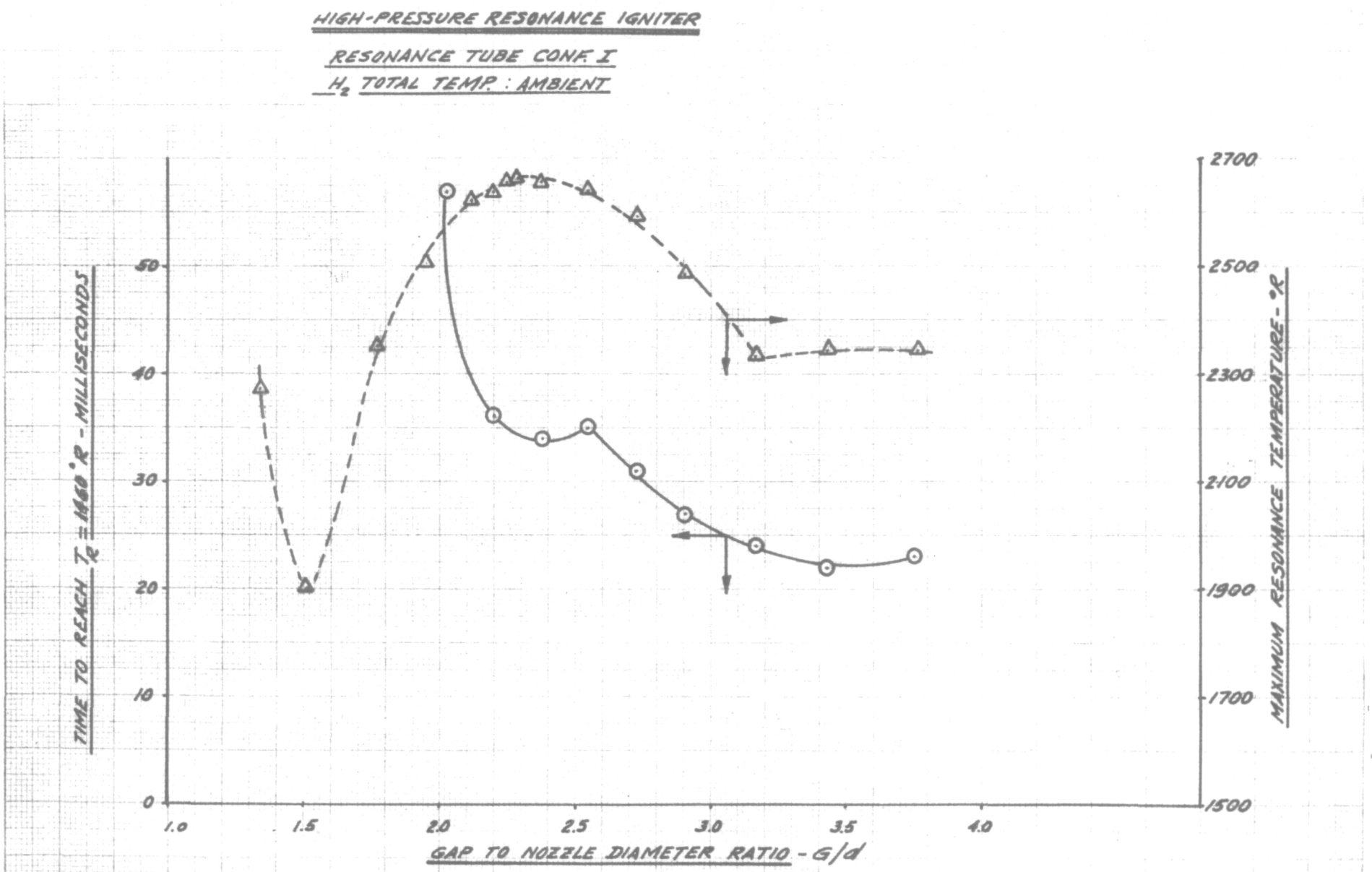

HIGH-PRESSURE RESONANCE IGNITER
RESONANCE TUBE CONF. I
H_2 TOTAL TEMP. : AMBIENT
TIME TO REACH T_R = M60 °R - MILLISECONDS
MAXIMUM RESONANCE TEMPERATURE - °R
GAP TO NOZZLE DIAMETER RATIO - G/d
0
10
20
30
40
50
1500
1700
1900
2100
2300
2500
2700
1.0
1.5
2.0
2.5
3.0
3.5
4.0

Figure 23

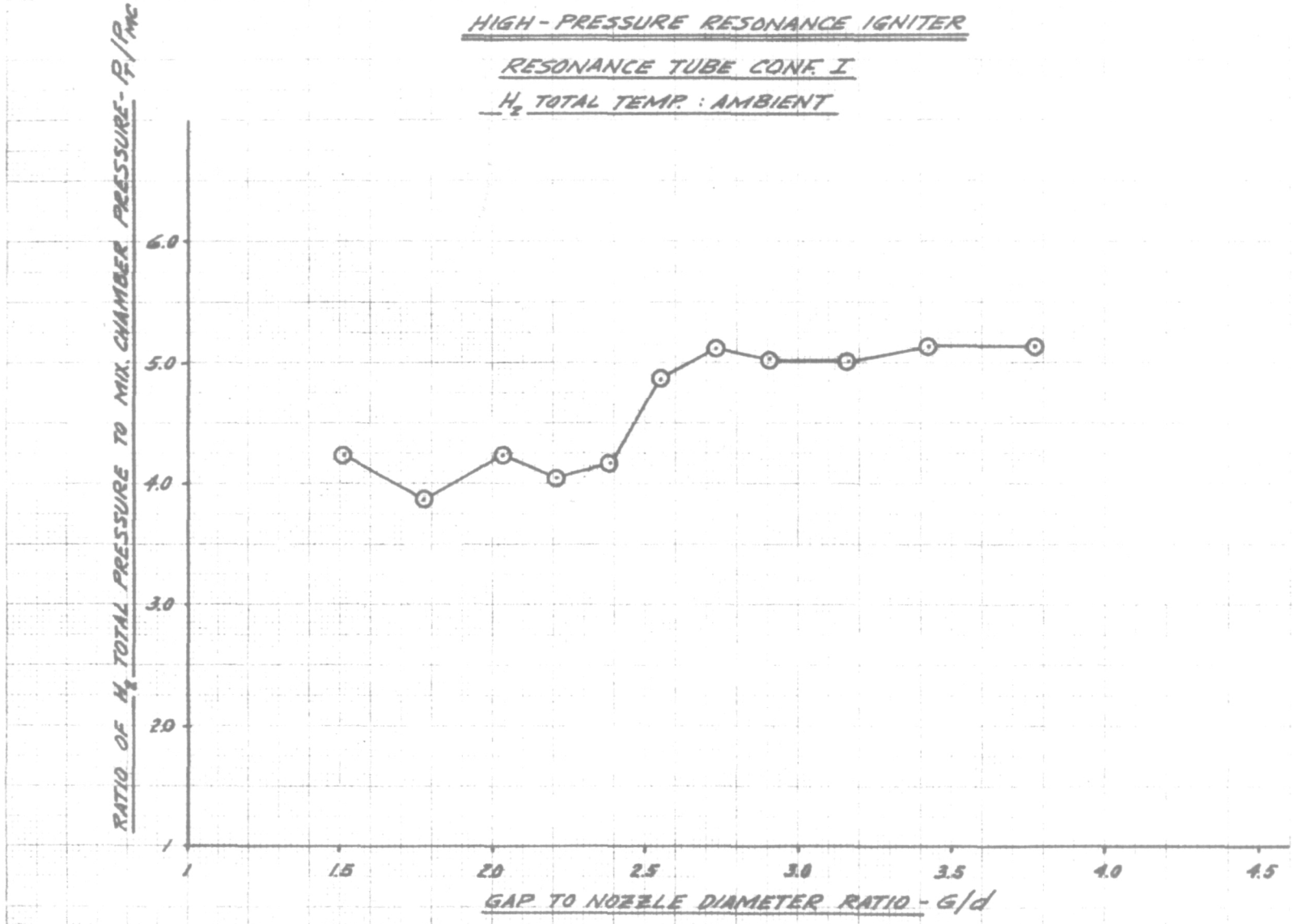

HIGH - PRESSURE RESONANCE IGNITER
RESONANCE TUBE CONF. I
H_2 TOTAL TEMP. : AMBIENT
RATIO OF H_2 TOTAL PRESSURE TO MIX. CHAMBER PRESSURE - P_T/P_{MC}
6.0
5.0
4.0
3.0
2.0
1
1
1.5
2.0
2.5
3.0
3.5
4.0
4.5
GAP TO NOZZLE DIAMETER RATIO - G/d

Figure 24

With configuration II resonance tube, following the same test procedure as described above, G/d was incrementally varied varied between 1.95 and 3.43, while P_T/P_{MC} was varied between 3.98 and 6.21. The optimum G/d to reach 1460 R in a minimum time (35 msec) was found to be 2.86, with a corresponding P_T/P_{MC} ratio of 5.37 as shown in Fig. 25.

Conclusions from Geometrical Characterization Tests. Since the resonance tube configuration I yielded a hydrogen temperature of 1460 R in a time period considerably less than the time required by configuration II to reach the same temperature (22 ms vs 35 ms), configuration I was chosen as the resonance tube geometry for the auto-igniter design to be tested during Task II of this program. For this design, the internal geometry of the resonance tube (configuration I) and both the optimized gap distance and fixed restriction throat diameter will be maintained.

System Characterization. A number of test series were run to determine the effect of various system variations on the hydrogen resonance temperature-time relation. The influences of the following variables were investigated: (1) hydrogen total temperature, (2) hydrogen total pressure, (3) presence of a large line volume (upstream of the hydrogen valve) caused by the introduction of the heat exchanger, and (4) small cavities at the end of the resonance tube resulting from the interfacing with the oxidizer valve hardware. Details of the system characterization tests will be discussed below.

Hydrogen Total Temperature. The resonance tube configuration II and a fixed gap (optimized during the geometry characterization tests - G/d = 2.86) were used throughout the test series. The inlet hydrogen total temperature ranged between 220 R (122 K) and 785 R (435 K). For every hydrogen temperature

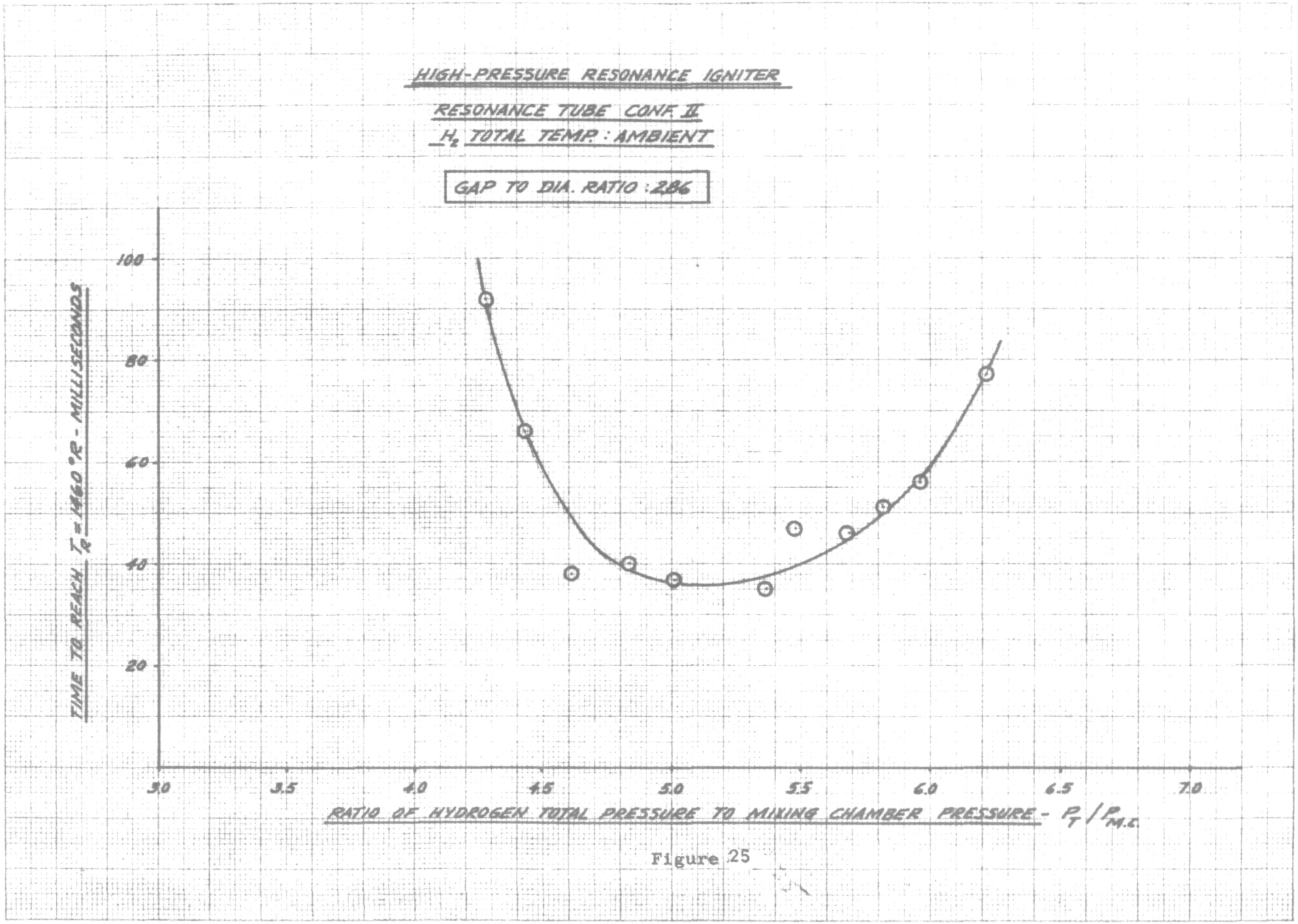

HIGH-PRESSURE RESONANCE IGNITER
RESONANCE TUBE CONF. II
H_2 TOTAL TEMP.: AMBIENT
GAP TO DIA. RATIO: 2.86
TIME TO REACH T_0 = 1460 °R - MILLISECONDS
100
80
60
40
20
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
RATIO OF HYDROGEN TOTAL PRESSURE TO MIXING CHAMBER PRESSURE - $P_T / P_{M.C.}$

Figure 25

condition, the steady-state pressure ratio (P_T/P_{MC}) was varied by modulation of the restriction valve.

Figure 26 indicates the highest measured resonance temperature as a function of the inlet hydrogen total temperature for two different time slices, 50 and 100 msec. It should be emphasized that the points shown in Fig.26 were obtained with a resonance igniter having a fixed gap and a single resonance tube configuration, and that the resonance temperatures indicated are for optimum pressure ratios (P_T/P_{MC}) which are different for each particular inlet hydrogen total temperature.

The resonance temperatures obtained with ambient inlet hydrogen total temperature (i.e., passing hydrogen through the heat exchanger without heating or cooling) appear to be out of line with the rest of the points obtained with temperature conditioned hydrogen. The principal reason for this deviation can be attributed to the fact that the fixed gap used for this test series was optimized during the resonance igniter geometry optimization test phase using ambient hydrogen. Thus, data in Fig.26 strongly suggests that the gap could be optimized for different inlet hydrogen total temperatures.

Another interesting aspect of this test series is the fact the maximum resonance temperature, obtained with ambient hydrogen going through the heat exchanger, is substantially lower than the maximum resonance temperature obtained with ambient hydrogen bypassing the heat exchanger. Here again the presence of the heat exchanger appears to have influenced the flowrate-time characteristics to cause a decrease in the maximum achievable resonance temperature. A short test series was run to evaluate the resonance temperature with and without heat

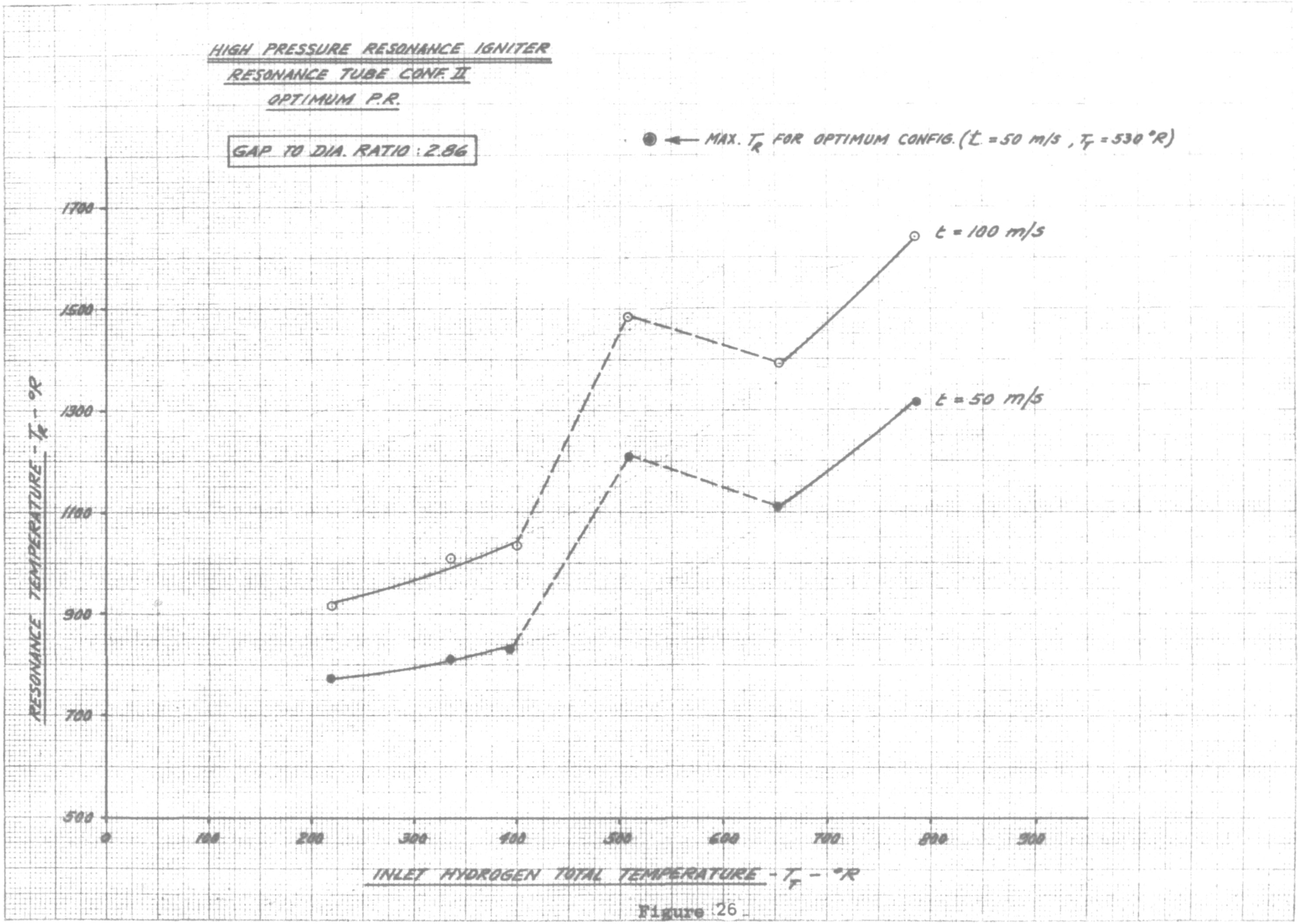

HIGH PRESSURE RESONANCE IGNITER
RESONANCE TUBE CONF. II
OPTIMUM P.R.
GAP TO DIA. RATIO : 2.86
● ← MAX. T_R FOR OPTIMUM CONFIG. ($\bar{t}$ = 50 m/s , T_T = 530 °R)
t = 100 m/s
t = 50 m/s
RESONANCE TEMPERATURE - T_R - °R
1700
1500
1300
1100
900
700
500
0
100
200
300
400
500
600
700
800
900
INLET HYDROGEN TOTAL TEMPERATURE - T_T - °R

Figure 26

exchanger in the hydrogen feed line. This data will be discussed below.

To summarize, high resonance temperatures can be obtained with conditioned hydrogen temperatures by optimizing the gap distance, the restriction area, and the flowrate-time characteristics for finite ranges of inlet hydrogen total temperatures.

Hydrogen Total Pressure. The test series run to investigate the effect of hydrogen total pressure on the resonance temperature was made with resonance tube configuration I, and with fixed gap (G/d = 3.426) and fixed restriction area (corresponding to P_T/P_{MC} = 5.2). The hydrogen inlet pressure was gradually reduced and the temperature was measured at the end of the resonance tube. Figure 27 shows the measured resonance temperature as a function of the hydrogen inlet total pressure after 50 and 100 msec of opening of the hydrogen valve.

Also shown on Fig.27 are the maximum hydrogen resonance temperatures measured during the low pressure igniter test series after 50 and 100 msec. These points were obtained with the resonance tube configuration III (scaled-up version of configuration I), and with an optimized gap (G/d = 2.7) and pressure ratio (P_T/P_{MC} = 4.65). Figure 27 indicates that the high pressure resonance igniter can operate satisfactorily at low pressures and that somewhat higher resonance temperature may be achieved by slight modifications of the gap distance and restriction orifice diameter.

Heat Exchanger Line Volume. As stated previously, during the hydrogen inlet temperature variation experiments it was observed that the presence of the heat exchanger in the test setup led to lower resonance temperatures than expected. This reduction in resonance temperature was especially evident when flowing ambient temperature hydrogen through the heat exchanger (no cooling or heating) and into the igniter hardware. An investigation was undertaken to

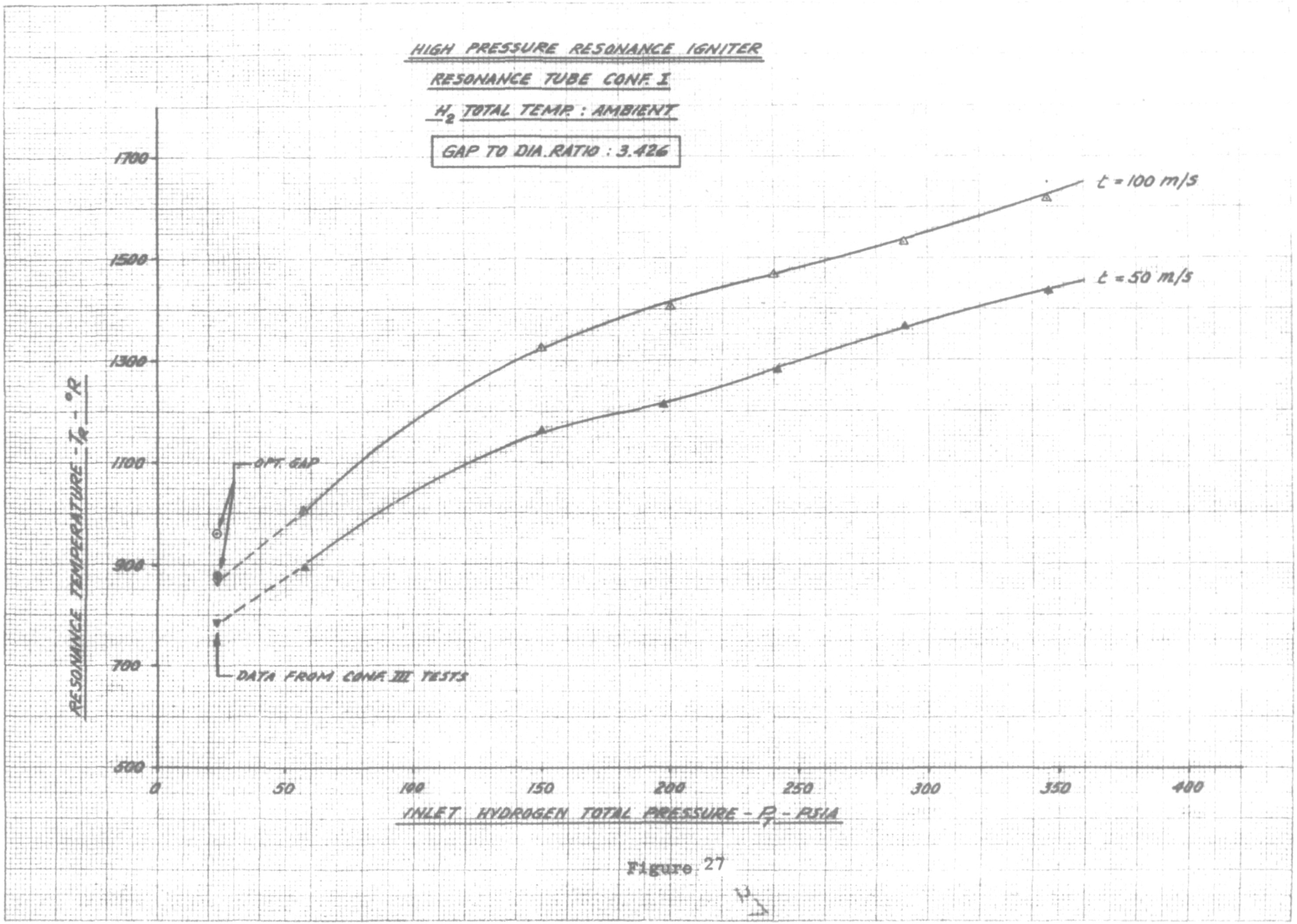

HIGH PRESSURE RESONANCE IGNITER
RESONANCE TUBE CONF. I
H_2 TOTAL TEMP. : AMBIENT
GAP TO DIA. RATIO : 3.426
t = 100 m/s
t = 50 m/s
0.1" GAP
DATA FROM CONF. III TESTS
RESONANCE TEMPERATURE - T_R - °R
INLET HYDROGEN TOTAL PRESSURE - P_T - PSIA
1700
1500
1300
1100
900
700
500
0
50
100
150
200
250
300
350
400

Figure 27

determine the reasons for this phenomenon. Test runs were made with ambient hydrogen flowing through the heat exchanger, and test runs were made with ambient hydrogen while bypassing the heat exchanger.

All tests were conducted with the resonance tube configuration I with a fixed gap (G/d = 3.426) and a variable restriction orifice (Annin valve). Figure 28 shows the results of two typical tests, one with the heat exchanger and one without the heat exchanger in the system. These two tests were chosen for comparative analysis mainly because both test runs had closely equal steady-state pressure ratios (P_T/P_{MC}), as shown on Fig. 28. Heretofore, it was believed that resonance configurations having geometric similarity and operating with gases of similar thermodynamic properties at equal pressure ratios would generate equal resonance temperatures. In a previous discussion it was pointed out that higher inlet total pressures led to higher resonance temperatures; yet, as shown on Fig. 28, the higher transient inlet pressure level of the hydrogen as it flows through the heat exchanger led to lower resonance temperature. The reasons for this phenomenon are attributable to the negative inlet total pressure gradient, and a plausible hypothesis can be made based on the physics of temperature generation within a resonance tube. Basically, the gas temperature rise occurs as a result of cyclic compressions and expansions corresponding to a "filling" and "emptying" process. Essentially, if the total pressure of the working medium is dropping, the compression phase (during any particular resonance cycle) occurs at a higher pressure than the successive expansion phase, the net effect being that part of the gas which has been compressed and has undergone a temperature rise "escapes" during the expansion phase. Thus, the mass fraction (or energy fraction) of the gas which "escapes" is greater

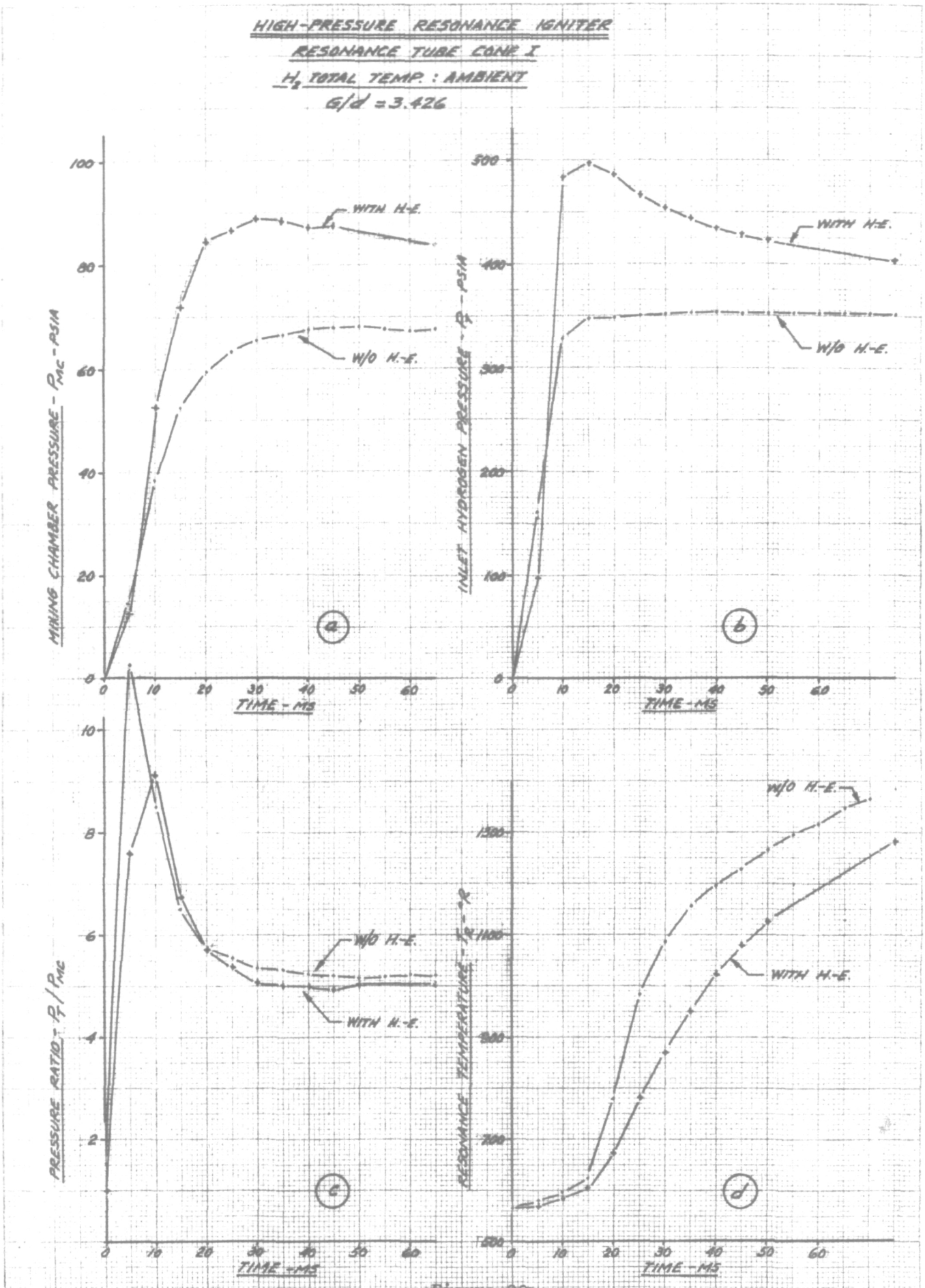
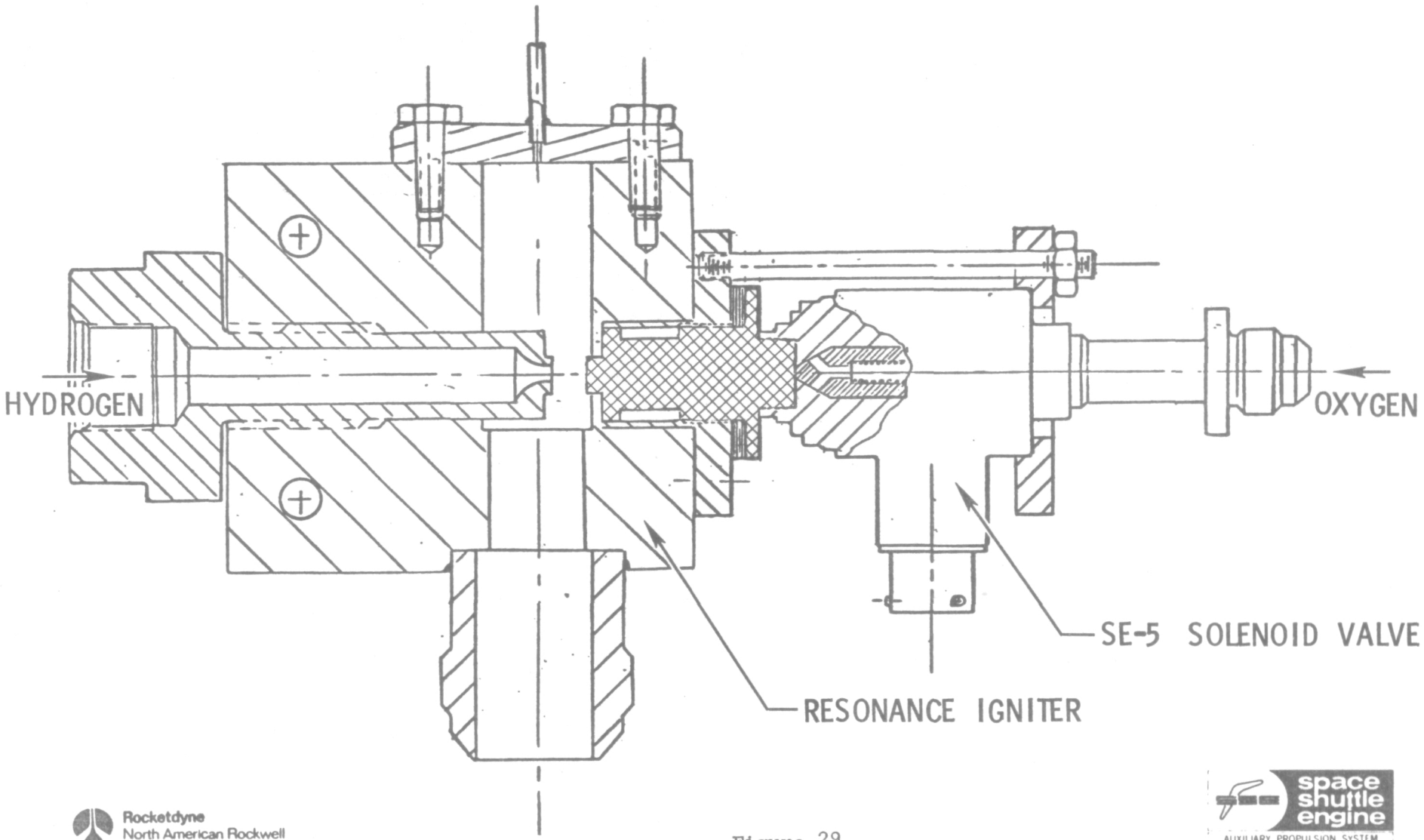

HIGH-PRESSURE RESONANCE IGNITER
RESONANCE TUBE CONF. I
H_2 TOTAL TEMP. : AMBIENT
G/d = 3.426
MIXING CHAMBER PRESSURE - P_{MC} - PSIA
INLET HYDROGEN PRESSURE - P_H - PSIA
PRESSURE RATIO - P_I / P_{MC}
RESONANCE TEMPERATURE - °R
TIME - MS
WITH H.-E.
W/O H.-E.
a
b
c
d

Figure 28

if the total pressure of the working gas is decreasing as compared to the case where the total pressure is increasing or remaining constant. Consequently, the resonance temperature generation is more efficient with a gradually increasing gas supply pressure than with a decreasing gas supply pressure. It is, therefore, recommended that in future tests gas injection pressures overshoots be reduced or eliminated.

Resonance Tube Cavities. In order to couple the quartz resonance tube with the oxygen valve (SE-5 valve), a metal case was fabricated to mate the quartz tube with the metal valve pintle. To prevent direct impact loads on the quarts, the casing included a metal seat for the pintle (see Fig. 29). This metal seat introduced added cavities to the resonance tube. Tests were conducted to determine the effect of these cavities on the resonance temperature-time relation. An SE-5 valve, modified to include a thermocouple, was placed at the end of the resonance tube configuration I. All tests were made with a fixed gap (G/d = 3.426) and fixed restriction area (P_T/P_{MC} = 5.2). Resonance temperatures were measured with various cavities and seals to prevent gas leakage into the labyrinths created by the quartz-metal contact. In general, it was found that additional volumes at the end of the resonance tube configuration shown on Fig.29 will cause substantial decreases in the measured temperatures attained by the hydrogen within a given time period. Introduction of a thin asbestos gasket placed between the end of the quartz tube and the metal casing successfully eliminated the labyrinth leakage and restored the resonance temperature-time relation to the level previously found during the geometry characterization test.

HIGH PRESSURE AUTO-IGNITER AND OXYGEN VALVE SCHEMATIC



Rocketdyne
North American Rockwell

Figure 29

space shuttle engine
AUXILIARY PROPULSION SYSTEM

Combustion Characterization Tests

One hundred and six tests were run with oxygen and hydrogen flowing through the high pressure resonance igniter hardware. Of the 106 combustion tests, 78 tests were conducted with ambient temperature propellants and 28 tests with propellants at conditioned temperatures. Of the ambient propellant tests, most tests were conducted at high injection pressures [near 375 psia (2.58×10^6 N/m^2)] and a series of tests were conducted at low injection pressures [near 75 psia (5.68×10^5 N/m^2)]. Ignition and sustained combustion was obtained at all propellant conditions, i.e., high and low injection pressures and conditioned temperatures.

For the entire combustion test series, the geometry of the igniter was fixed, i.e., the gap, restriction area (the Annin valve was replaced by a sonic nozzle), and a resonance tube geometry (configuration I) remained unaltered. The gap and restriction area were set at the dimensions dictated by the results of the test series described previously (i.e., geometry designed to optimize resonance temperature of hydrogen at ambient temperature). The basic ignition test procedure consisted of (1) opening the hydrogen valve (Marotta) prior to opening of the oxygen valve (SE-5), (2) establishment of steady O_2/H_2 flow for a period of several hundred milliseconds, and (3) oxygen valve closing followed by hydrogen valve closing.

The time differential between opening the hydrogen valve and opening of the oxygen valve (hydrogen lead) was varied between 4 and 25 milliseconds. Repeated ignition was obtained even at the shortest hydrogen lead, pointing out the distinct possibility that the highest temperature in the resonance cavity does not necessarily occur at the closed end of the cavity where the thermocouple was located during the previously described test series.

The mixture ratio (O_2/H_2) ranged between 0.21 and 1.5. Even at the lowest mixture ratios, ignition and combustion were sustained for the duration of propellant flow. Again, the fact that these low mixture ratios ignited suggests the existence of resonance temperature higher than those measured at the end of the cavity.

The response time (defined as time of signal to hydrogen valve to time of pressure buildup to 90 percent of final combustion chamber pressure) remained, for most tests, below 50 milliseconds. In a test series run with a stainless steel resonance tube having exactly the same geometry as the quartz resonance tube, the response time remained below 30 milliseconds.

Nearly all tests conducted with high pressure and ambient temperature propellants resulted in ignition and sustained combustion. The frequency of ignition was reduced mainly for those tests with mixture ratios above 0.9. The reasons for the reduced ignition frequency for mixture ratios above 0.9 may be explained by the fact that increasing mixture ratios were obtained by increasing the oxygen supply pressures, thus reducing residence time for the O_2/H_2 mixture within the resonance tube.

The influence of increasing the oxygen flowrate (keeping the hydrogen flowrate nearly constant), or reduced residence time, is also demonstrated on a plot of energy release efficiency (c* efficiency) vs mixture ratio (see Fig. 30). It should be noted that the data points shown on Fig.30 are from the test series run with ambient propellants with the hydrogen injection pressures at or near 375 psia (2.585×10^6 N/m^2). The decreasing trend of energy release efficiency with mixture ratio indicates that the operation of the resonance

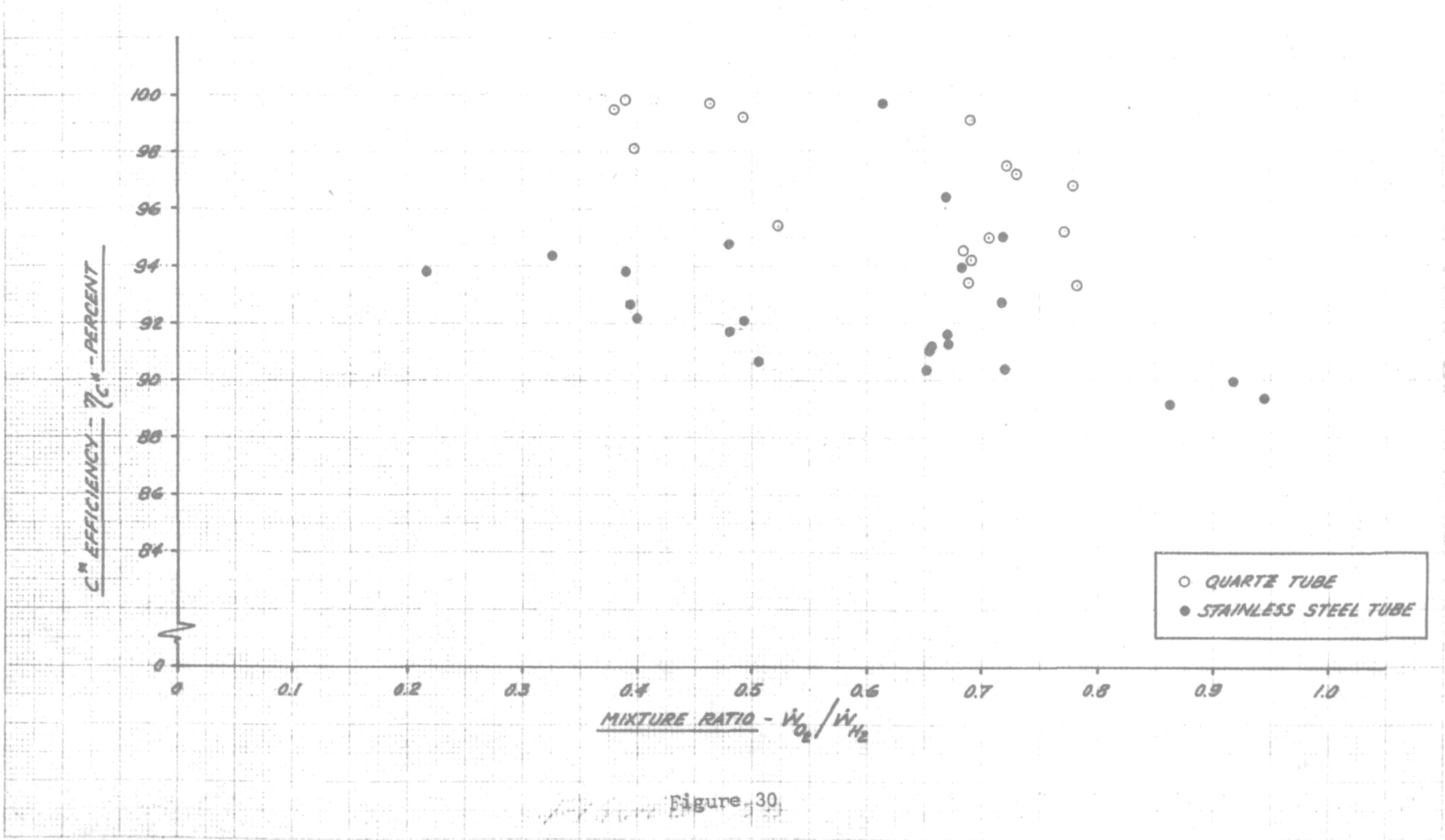

HIGH - PRESSURE RESONANCE IGNITER
RESONANCE TUBE CONF. I
O_2 & H_2 TOTAL TEMP. : AMBIENT
G/d = 3.426
C^* EFFICIENCY - η_{C^*} - PERCENT
100
98
96
94
92
90
88
86
84
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
MIXTURE RATIO - $\dot{W}_{O_2}/\dot{W}_{H_2}$
QUARTZ TUBE
STAINLESS STEEL TUBE

Figure 30

igniter may be mixture ratio limited and that secondary oxygen augmentation will be required to achieve high mixture ratio combustion.

From the present data analyzed, it appears that in order to achieve reliable auto-ignitions with low propellant temperatures and pressures, the resonance igniter should be run at mixture ratios below 0.9 and that if increased mixture ratios are desired it be accomplished by means of secondary oxygen augmentation, i.e., oxygen injection at the exit plane of the resonance igniter mixing chamber.

Tables 4, 5, and 6 list all of the combustion tests run during Task I. Table 4 is a listing of the combustion tests run with ambient temperature propellants and with the hydrogen injection pressures at or near 375 psia (2.585×10^6 N/m^2). Table 5 is a listing of the tests run with variations of propellant temperatures [from ambient down to 285 R (158.4 K)]. Table 6 lists the tests run with propellant injection pressure variations H_2 pressures from 346 psia (2.386×10^6 N/m^2) to 83 psia (5.723×10^5 N/m^2).

Design Conclusions and Recommendations

During the Task I effort on auto-ignition phenomena investigations, the geometrical parameters, system and combustion characteristics of the resonance igniter were determined.

Hydrogen resonance temperatures sufficient for ignitions of O_2/H_2 mixtures were achieved in time periods considerably less than 50 msec [time from valve opening, for H_2 at ambient temperature and pressures of approximately 375 psia (2.58×10^6 N/m^2)] with the resonance tube configuration I, a gap of 0.394 in. (1.00 dm) and a restriction orifice diameter of 0.260 in. (0.660 cm).

TABLE 4

O_2/H_2 COMBUSTION TESTS

TEST NO	TOTAL FLOWRATE LB/SEC	MIXTURE RATIO	MIXING CHAMBER PRESSURE - P_{MC} PSIA	REMARKS
243	0.0366	0.381	147.2	1) H_2 and O_2 at ambient temperatures
244	0.0370	0.391	150.4	2) Quartz resonance tube: tests 243 to 260
245	0.0372	0.398	148.6	3) Stainless-steel resonance tube: tests 261 to 284
246	0.0360	0.463	149.7	
247	0.0373	0.492	155.7	
248	0.0384	0.523	155.7	
249	0.0399	0.683	166.8	
250	0.0407	0.688	168.5	
251	0.0402	0.689	167.9	
252	0.0401	0.692	176.3	
253	0.0408	0.699	101.1*	
254	0.0411	0.705	173.4	
255	0.0413	0.713	184.1	
256	0.0403	0.722	175.1	
257	0.0412	0.731	178.7	
258	0.0411	0.772	176	
259	0.0411	0.779	179.1	
260	0.0410	0.782	172.6	
261	0.0302	0.213	106.1	
262	0.0326	0.325	121.7	
263	0.0345	0.389	131.6	
264	0.0346	0.395	130.5	
265	0.0348	0.400	130.9	
266	0.0356	0.481	139.6	
267	0.036	0.482	138.6	* No ignition due to facility operation sequencing error (N_2 purge gas residual in igniter)
268	0.036	0.494	139.4	

TABLE 4 (CONT'D)

TEST NO.	TOTAL FLOWRATE LB/SEC	MIXTURE RATIO	MIXING CHAMBER PRESSURE - P_{MC} PSIA	REMARKS
269	0.0363	0.506	139.3	
270	0.0367	0.617	159.2	
271	0.0381	0.649	151.1	
272	0.0377	0.653	150.7	
273	0.0376	0.656	150.6	
274	0.0385	0.667	163.1	
275	0.0376	0.669	151.7	
276	0.0376	0.671	151.4	
277	0.0380	0.681	158.0	
278	0.0395	0.717	162.8	
279	0.0389	0.721	156.2	
280	0.0423	0.839	106.3**	
281	0.0404	0.862	166.5	
282	0.0424	0.868	100.1**	
283	0.0414	0.917	171.13	
284	0.0412	0.943	170.3	
				** No ignition

TABLE 5

O_2/H_2 COMBUSTION TESTS - PROPELLANT TEMPERATURE VARIATION

TEST NO.	TOTAL FLOWRATE LB/SEC	MIXTURE RATIO	MIXING CHAMBER PRESSURE - P_{MC} PSIA	O_2 TEMP °R	H_2 TEMP °R	REMARKS
285	0.0382	0.92	160	576	530.5	1) Quartz resonance tube: all tests
286	0.0386	0.93	160.5	576	530	
287	0.0379	0.933	160	577.5	531	
288	0.0383	0.934	161	575.5	530	
289	0.0389	0.97	161	577.5	531	
290	0.0395	1.015	93 *	576.5	530.5	
291	0.0385	0.975	145	526	528.5	
292	0.0385	0.975	148	528.5	526.5	
293	0.0393	0.985	149	526	529	
294	0.0387	0.72	171	412	411	
295	0.0402	0.787	156	413	414.5	
296	0.0430	0.912	94.5 *	414	416	
297	0.0431	0.917	94 *	412.5	412.5	
298	0.0435	0.835	163	358	363	
299	0.0462	0.95	96 *	358	363	
300	0.0465	0.975	95.5 *	355	362	
301	0.0465	0.979	95.5 *	356	382.5	
302	0.0513	1.155	146	340.5	351	
303	0.0516	1.188	147	343	346	
304	0.0527	1.27	146.5	303	380	* No ignition

TABLE 5 (CONT'D)

TEST NO.	TOTAL FLOWRATE LB/SEC	MIXTURE RATIO	MIXING CHAMBER PRESSURE - P_{MC} PSIA	O_2 TEMP °R	H_2 TEMP °R	REMARKS
305	0.0507	.928	165	284	300	
306	0.0530	1.0	99.8 *	281	295	
307	0.0530	1.023	100.2 *	308	281	
308	0.0572	1.187	103.5 *	308	284	
309	0.0562	1.230	99.5 *	285	319	
310	0.0560	1.240	103 *	282	318	
311	0.0560	1.240	99.5 *	285	331	
312	0.0587	1.284	178	284	317	
313	0.0595	1.297	150	285	318	
314	0.0597	1.235	147.5	285	274	
315	0.0613	1.359	148.5	285	293.5	
316	0.0648	1.50	98.5 *	286	296	*No ignition

TABLE 6

O_2/H_2 COMBUSTION TEST - PROPELLANT PRESSURE VARIATION

TEST NO.	TOTAL FLOWRATE LB/SEC	MIXTURE RATIO	MIXING CHAMBER PRESSURE - P_{MC} PSIA	O_2 PRESS PSIA	H_2 PRESS PSIA	REMARKS
317	0.0309	.411	112.5	323.7	343	1) H_2 and O_2 at ambient temperatures
318	0.0305	..426	114.7	327.2	343	
319	0.0310	.456	114.7	327.5	339.5	2) Quartz resonance tube
320	0.0336	.563	132.5	361.7	346.5	
321	0.0337	.567	133.5	361.5	346.5	
322	0.0344	.592	133.5	361.7	343.4	
323	0.0374	.685	148	381		
324	0.0378	.71	148.5	381	343	
325	0.0396	.887	146.5	380	337	
326	0.0476	1.152	191.5	470	344	
327	0.0468	1.208	193.5	479.3	343.6	
328	0.0471	1.21	191.4	473.3	335.5	
329	0.0458	1.235	200.7	473	335	
339	0.022	.964	88.8	223.4	179.4	
340	0.0221	.99	88.9	223.2	177.4	
341	0.0224	1.035	52.4 *	222.3	176.8	
342	0.0219	1.047	88.6	223.4	175.7	
343	0.0090	.667	23.4 *	87.1	88.6	
344	0.0116	1.18	26.3 *	120.1	85.6	
345	0.0116	1.23	25.9 *	119.4	84.9	
346	0.0113	1.26	25.5 *	120.1	83	
347	0.0130	1.451	51	148.1	88.2	
348	0.0131	1.472	28.4 *	147.9	87.6	
349	0.0132	1.491	51.8	148.2	88.7	* No ignition

For a geometrically optimized igniter, it was found that hydrogen inlet pressure overshoots increased the time required to reach a given resonance temperature.

Combustion of O_2/H_2 was achieved over a wide range of mixture ratios (0.21 to 1.5), propellant temperatures and pressures. During the 106 combustion tests performed, nearly perfect ignition frequency occurred for mixture ratios below 0.9.

Based on the above results, it was concluded that the following guidelines be incorporated into the Task II - auto-ignition investigation phase:

1. The dimensions for the resonance igniter should be consistent with the results of the geometrical characterization tests (resonance tube configuration I) performed under Task I.
2. Test facility modifications should be made to preclude pressure overshoots of the propellants flowing into the igniter.
3. The interface between the igniter and the oxygen valve should be designed to exclude additional volumes at the end of the resonance tube.
4. To insure reliable ignitions, combustion test should be run at O_2/H_2 mixture ratios below 0.9.
5. Tests should include a method of oxygen augmentation in order to obtain higher combustion gases energy levels while providing a means of cooling the mixing chamber.

AUTO-IGNITER DESIGN AND FABRICATION

During this report period, the design and fabrication of the auto igniter to be used in Task II tests were completed. The design was based upon the phenomena test results discussed above. A detailed design report was submitted to NASA and approved. In the following paragraphs, the major aspects of this

design will be discussed. Also to be discussed are the results of the heat transfer analysis upon which the design was based.

Hardware Description. Figure 31 shows the assembly of the Task II resonance igniter. The hydrogen nozzle has a rounded entrance ending sharply at the throat. A portion of the outer surface of the nozzle will be exposed to combustion gases; however, it is cooled by the hydrogen flowing through it and protected by the flow pattern of the jet. Testing with the phenomena hardware indicated only minor heating of this surface. The nozzle assembly incorporates the use of spacers for precise setting of the expansion gap. This also allows adjustment for proper tuning with different resonance cavities or cavities of different materials. The nozzle is short-coupled to reduce fill time and has straight-through flow for good injection characteristics.

The mixing chamber provides flow area away from the resonating jet during the start transient and serves as a combustion-mixing chamber during steady-state operation. Flow area around the expanding jet is required to remove the reflected gas without distorting the jet and deflecting it away from the resonance cavity entrance. The mixing chamber diameter (0.750 in.) was found to be adequate in the phenomena hardware. During steady-state operation, the chamber contains the highly turbulent combustion gases and, based upon the hot firing of the phenomena hardware, some cooling is required. The cooling requirement is expected to be most severe in the quadrant centered about the oxygen orifice entrance (resonance cavity entrance). Due to the high sonic velocity of hydrogen and the low mixture ratios of operation, the momentum of the hydrogen jet is several times that of the oxygen jet exiting the resonance cavity. Thus, the oxygen flow tends to be folded back to the chamber wall with a bias toward the chamber exit. The oxygen will flow around and down

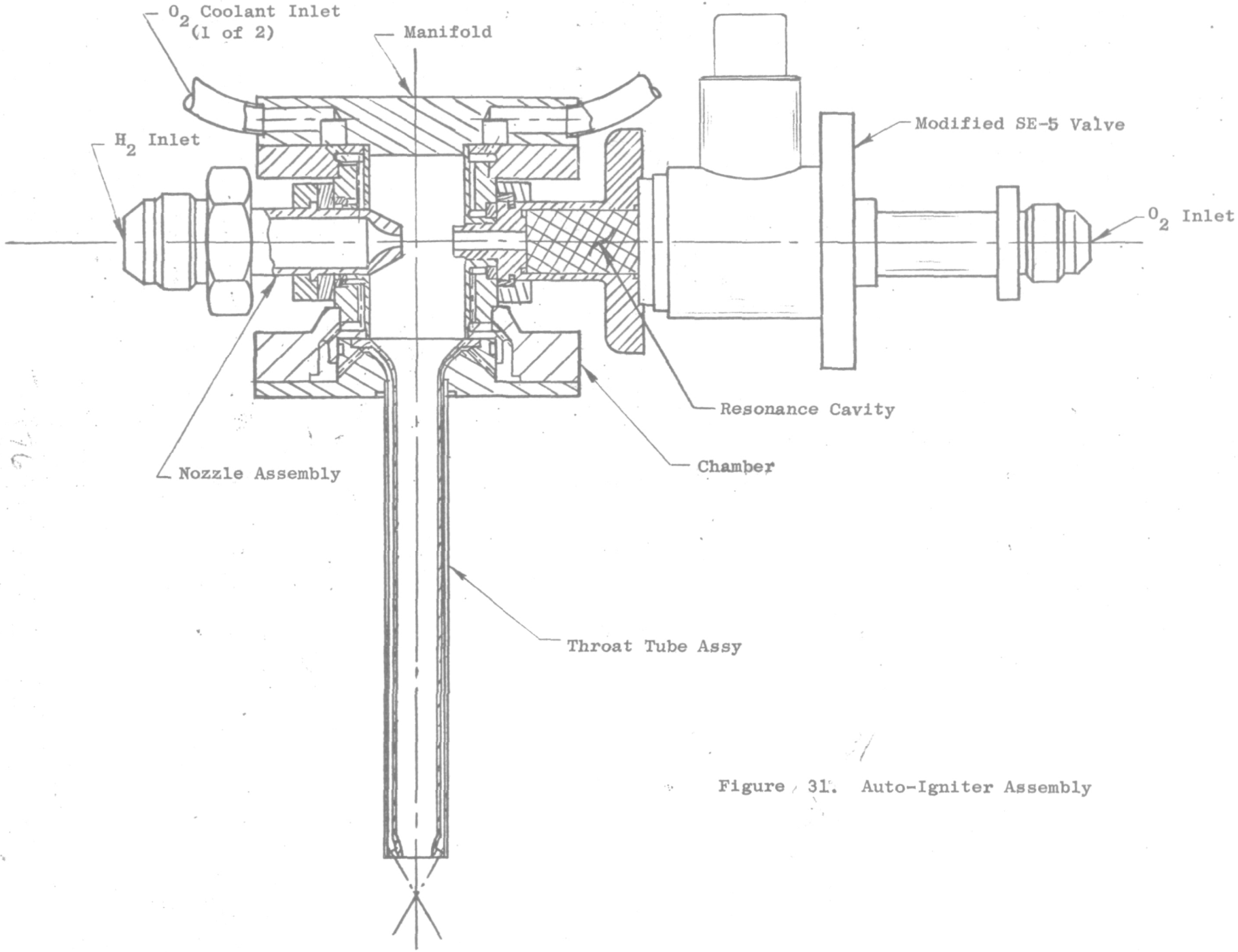


Figure 31. Auto-Igniter Assembly

the chamber as it mixes and burns with the hydrogen; thus, the least heating is expected above the axis of the jet (away from the throat) and in the quadrant centered about the hydrogen nozzle.

The mixing chamber is cooled by forced convection with an oxygen dump cooling circuit in series with the throat. The flow circuit for the cavity starts with a double entrance tapered manifold which distributes the flow around the top of the cavity and through the top flange where it enters a manifold directly above the coolant passages. The coolant passages are formed by drilling parallel to the wall. On the hydrogen nozzle side, the passages are located at 20-degree increments (8 passages). The diameter is 0.0469 inches and the minimum wall thickness is 0.030 inches. The oxygen entrance side has passages located at 15-degree increments (13 passages); these are 0.062 inches in diameter and have a wall of 0.0030 inches. Where both the resonance cavity and the nozzle project through the wall, the passages are drilled from both ends into an annular cavity concentric with the nozzle or resonance cavity. The annular cavity is formed by hollow milling around the entrance and brazing a ring over the outside. Only parent metal is on the inside surface precluding a leak of oxygen into the chamber around either port. The annular passage provides continuity of flow around the disruption in the chamber wall. Since the turning will produce added pressure drop, two extra holes into the annular cavity are provided in the upper half of the chamber on the resonance cavity side. Since the holes are radially removed from the chamber wall, they do essentially no cooling in the upper half but do enhance the cooling capability of the passages directly below since the flow will be increased. Similar features were not incorporated on the hydrogen nozzle side because of the reduced heating and the lower availability of coolant. The

port through the chamber is threaded for the resonance cavity entrance to screw in; it will be cooled by conduction as well as by convection by the oxygen flowing through it. The flange on each end of the chamber is welded in place. At the bottom of the mixing chamber, the oxygen flows through the flange in a manner similar to the way it entered at the top.

The interface between the throat tube and the mixing chamber is designed to achieve two requirements. First, the seal between the oxygen and combustion products is surrounded by the coolant flow and removed from the elevated temperature of the hot gas wall. Secondly, the coolant flow is directed toward, and has access to the extreme corners at the joint leaving no exposed surface uncooled.

The throat tube is designed to interface with the APS high pressure injectors. The coolant circuit for the throat tube is a double wall design. The coolant is turning as it contacts the hot gas wall in the contraction. To permit expansion of the hot gas wall relative to the outer tube, a sliding joint is provided at the upper end with a seal between the main injector and the tube. The oxygen coolant exiting through orifices at the end of the tube will be injected into the hot gas to augment the igniter flow. The mixture ratio is more than tripled and provides a hotter gas for ignition of the main injector.

An uncooled throat tube and an uncooled chamber L* extension are included in the design. Although they are not shown in the basic assembly, the uncooled throat tube will permit independent cooling of the chamber. Use of the uncooled throat in a thrust chamber assembly permits short duration tests of nominal ignition characteristics. The uncooled chamber L* spacer may be used to increase the L* to the value tested in the phenomenon hardware.

If the chamber volume is found to be a significant parameter, then a spacer may be converted to a cooled spacer by boring the diameter and drilling feed passages from the manifold. A nickel liner would be inserted and brazed at each end to form simple double-wall coolant circuit.

The resonance cavity holder is a tubular section. It is threaded into the chamber with the protruding section being cooled by conduction to the chamber through the threaded base and by convection to the oxygen flowing through it. The hot gas seal is by the O-ring on the outer face of the chamber. Two bolts hold the cavity section to the hydrogen nozzle with the chamber between. The oxidizer valve will be a modified SE-5 valve. The valve has a teflon seal seating directly on the polished end of the resonance cavity. Other valve/seat configurations will be evaluated in combination with several small valves currently available at Rocketdyne.

The cavity parts are replaceable as a unit or in steps. Possible materials for the cavity include quartz, steel and a zirconia material. In addition, a thermocouple holder will be fabricated and attached to the end of the resonance tube during the initial test phase. The thermocouple measurements will allow fine tuning for minimum response time and provide the performance of the various steps and materials.

Heat Transfer Analysis. A thermal analytical model was developed; inputs into this program included the resonance igniter geometry, combustion gas and coolant gas transport and thermodynamic properties. The results of the heat transfer analysis are presented below.

1. Uncooled igniter only or igniter thruster operation is feasible for tests of less than 2 seconds duration.
2. Longer durations can be achieved by utilizing oxygen as coolant in surrounding ports or a coolant jacket.
3. Accumulated durations of indefinite time can be achieved by pulsing operation if cooldown is allowed between pulses.
4. Indefinite life and operating duration can be achieved if the nickel wall is maintained below 900° F. It is recommended that empirical data be generated to establish the actual limit as operation for long durations may be practical at wall temperature as high as 1200° F.
5. To maintain the maximum wall temperature below 900 F, 0.080 lb/sec coolant is required for 0.040 lb/sec hot gas at a mixture ratio of 1.0.
6. Indefinite operation is feasible if the hot gas mixture ratio is reduced to 0.8 and flowrate reduced to 0.036 lb/sec in conjunction with an oxygen coolant flowrate of 0.054 lb/sec.
7. The proposed design is predicted to operate indefinitely, either as an igniter only or in conjunction with the thruster utilizing oxygen coolant and igniter hot gas characteristics as stated in the preceding conclusion.

Auto-Igniter Fabrication

Fabrication of the auto-igniter hardware was completed on schedule. The basic igniter assembly is shown in Fig. 32. The optional igniter adapter incorporating oxidizer cooling/augmentation is shown in Fig. 33. The igniter will be tested in both configurations during Task II "igniter only" testing.

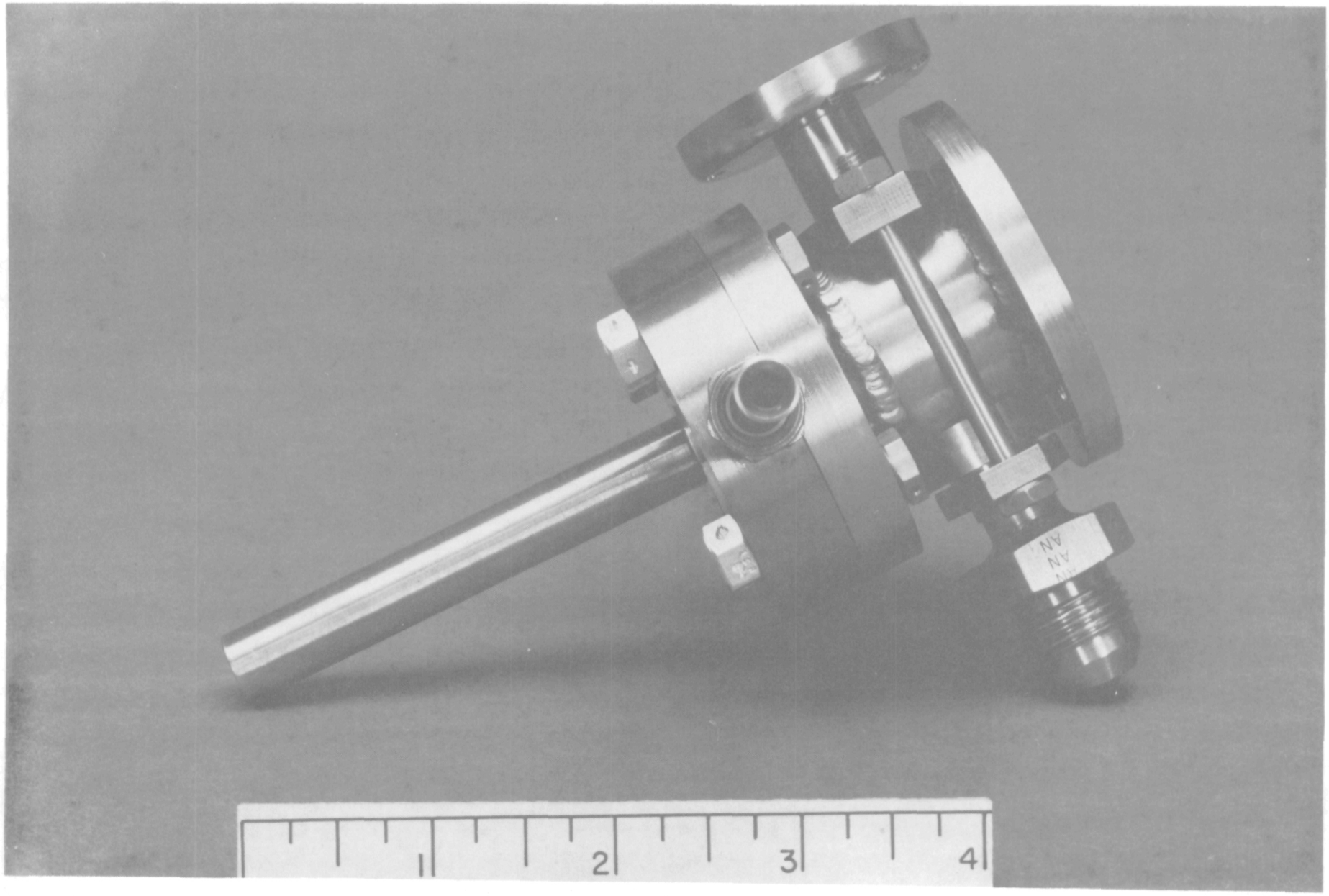


Figure 32. Auto Igniter Assèmbly

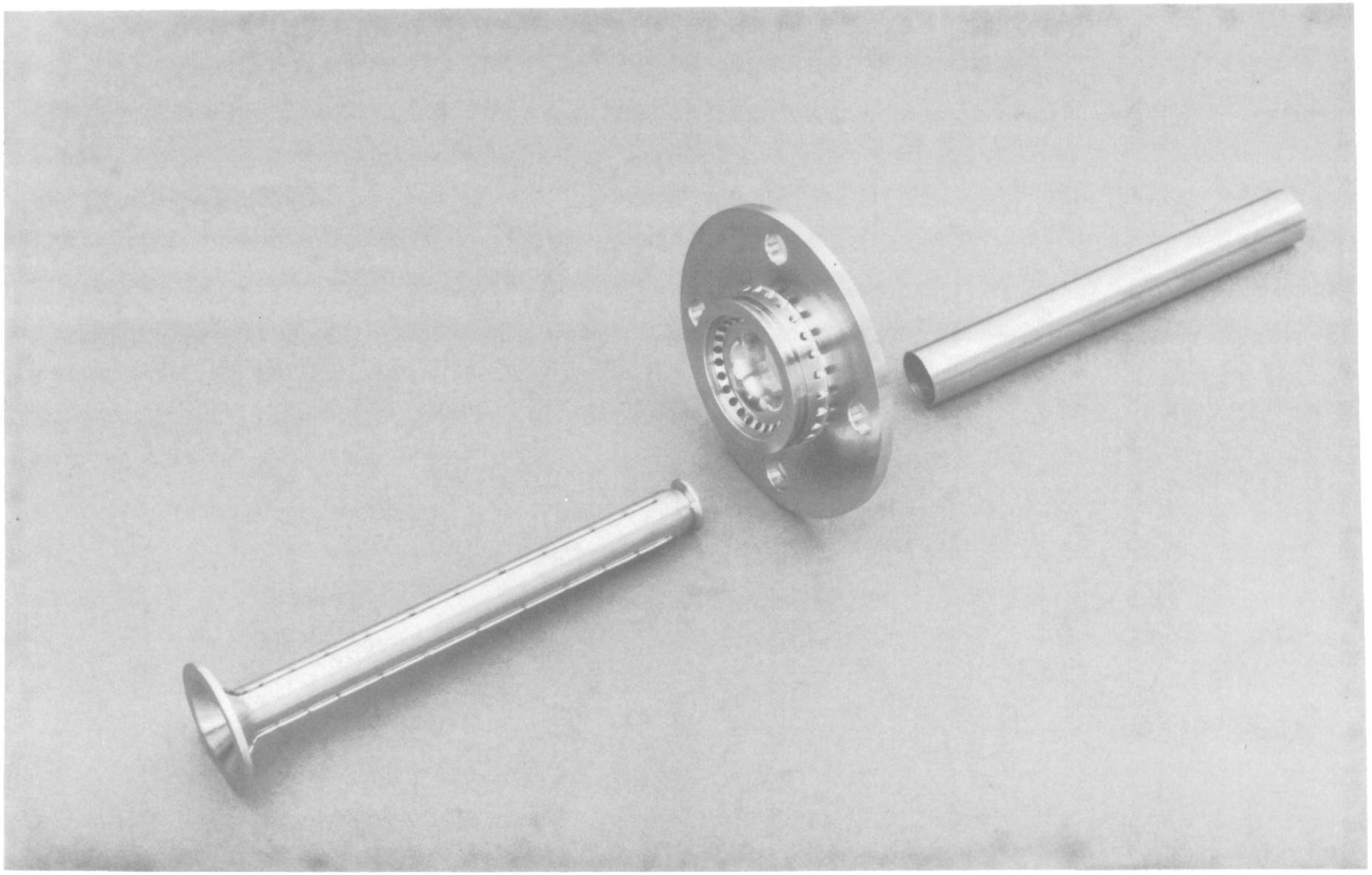


Figure 33. Optional Igniter Adapter (Oxidizer Cooling/Augmentation)

TASK II - IGNITER TESTS

During Task II, a series of hot-firing tests with gaseous hydrogen-gaseous oxygen propellants will be conducted using the igniters designed and fabricated in Task I. The test program is comprised of three different types of testing.

The "igniter only" testing will be conducted on both high and low pressure spark and resonance igniters at the Los Angeles Division to evaluate igniter ignition over the range of propellant inlet conditions. Operating limits including pressure, temperature, and sequencing will be established. These test results will provide design criteria and operating limits for the system design (Task III).

Igniter/thruster igniter tests will be conducted at SSFL CTL-IV to assure that igniter energy is sufficient to provide rapid ignition of the main propellants. These test results will provide thruster transients (ignition delay) data as a function of igniter flowrate and mixture ratio (energy).

Based upon the previous test results, a final test series will be conducted during the ninth month of the program to demonstrate igniter durability. The igniter and test conditions will be specified by NASA and 2500 successive ignition tests will be conducted.

During this report period, the "igniter only" test programs on both the low pressure and high pressure spark igniters were successfully completed. The test preparations for the "igniter only" test program for the auto igniter were completed and testing was initiated.

SPARK IGNITER TESTING

The spark igniter only testing was conducted on both high and low pressure configurations at the Los Angeles Division Thermodynamics Laboratory to evaluate igniter ignition over the range of operating conditions. Operating limits included pressure, temperature, sequencing and inductive spark energy. These test results will be used to establish design criteria and operating limits for the system design (Task III).

The low pressure and high pressure igniters were tested per the test plan submitted 20 November 1970. Both igniters meet their design objectives and demonstrated the capability to ignite over a wide range of propellant inlet conditions with spark energies well below the design goal of 30 millijoules stored. Igniter only testing and subsequent data analysis has been completed and the results are discussed separately in the following sections.

Objective

This test series was performed to determine the operating characteristics of the high and low pressure ignition systems. A principal goal was to determine the practical minimum electrical energy requirement which will enable small, compact, well-shielded exciter and spark plug units to be developed. This reduction in energy and size will minimize weight and RFI. During this Task II igniter only test effort, energy level requirements were established with a variable energy exciter. During the succeeding igniter/thruster tests, the feasibility of integrated plug/exciter unit will be demonstrated and RFI data will be obtained.

The igniter only spark tests were performed using gaseous hydrogen and gaseous oxygen propellants with the igniter exposed to vacuum conditions prior to each start. The igniters were instrumented to measure transient and steady-state values of critical temperatures and pressures. Ignition delay time and pressure and temperature response of the effluent gas from the igniter were determined. Operating limits including pressure, temperature, and minimum spark energy were established. The plug type selected from Task I (0.025 in. Dual Recessed Gap) was evaluated under hot-fire conditions. These test results will provide design criteria and operating limits for the Task III ignition system design.

Test Matrix

The test matrix for the spark igniter is presented in Table 7 and this matrix was applied to both high pressure and low pressure igniters. Three phases of tests are shown: (1) igniter evaluation, (2) spark energy evaluation, and (3) operational limits determination.

Igniter Evaluation. Two spark plug locations were evaluated to determine at which location the most favorable ignition condition occurs. Ignitability was determined by operating at lower overall mixture ratio and energy levels until ignition could not be obtained. Nominal operating conditions were a chamber pressure of 200 psia (138 N/cm^2) or 15 psia (10.35 N/cm^2), a flowrate of 0.04 lb_m/sec (0.018 kg/sec), a mixture ratio of 1.0:1 (o/f), and ambient temperature propellants. A J-2 type spark plug was used during these initial tests in which the igniter combustion characteristics were ascertained.

Spark Energy. The minimum spark energy required for reliable ignition and the spark plug selected during Task I was evaluated. Variables were spark energy

TABLE 7

SPARK IGNITER TEST PROGRAM

(Planned)

Test Matrix for High Pressure and Low Pressure Spark Igniters

Test Phase	Plug Type	Variables	Data & Points	Results
Igniter Evaluation	J-2	Plug Location (2) Energy Level (3) Mixture Ratio (3)	18	Igniter Operation Plug Location
Spark Energy	Selected	Energy Level (4) Mixture Ratio (2) Plug Location (2)	16	Plug Type Ignition vs. Energy Ignition vs. MR Location
Operational Limits		Spark Rate (3)	3	Ignition Delay vs. Rate
		Flowrate (2) Energy Level (3)	6	Ignition vs. $\dot{W}$ (P_c = Const.) Ignition vs. P_c ($\dot{W}^c$ = Const.) Energy vs. P_c Energy vs. $\dot{W}^c$
		Throat Area (1) Flowrate (2) Energy Level (3)	6	
		Temperature (4) Energy (3)	12	Ignition vs. Temperature Energy vs. Temperature

and mixture ratio. Minimum electrical energy for ignition was established. The spark plug location which could ignite at the lowest energy level and mixture ratio was selected for continued evaluation.

Operational Limits. The sensitivity of the combustor and spark ignition system to inlet conditions was investigated. Parameters which were systematically investigated were flowrate, pressure, throat area, spark rate, sequencing, and propellant temperature. The influence of these parameters upon minimum energy requirements was determined. Spark voltage and current discharge characteristics were monitored on selected tests to determine delivered spark energy under hot-fire conditions. These results were compared to Task I laboratory tests and were used to select the design point for the integrated plug/exciter unit.

Facility Description and Operation

The igniter test effort was conducted at the Los Angeles Division Thermodynamics Laboratory. A schematic of the high pressure propellant system is shown in Fig. 34, and the low pressure propellant system is shown in Fig. 35. Both propellant systems are common from the propellant supply through the heat exchangers.

Propellant Systems. Feed systems for both propellants are similar in size and configuration. The propellant is stored in high pressure bottles and is supplied through a 1-1/2-inch (3.8 cm) system and pressure regulator to the test cell. A calibrated sonic venturi is incorporated with a bypass line and valve. This feature is a convenient method of calibrating the facility, igniter hardware and subsonic flowmeters. During blowdowns, the bypass valve is closed and flow is measured and controlled by the sonic venturi while system/hardware parameters are measured. During the ignition tests, the bypass valve is opened and the effect of the sonic venturi is negated.

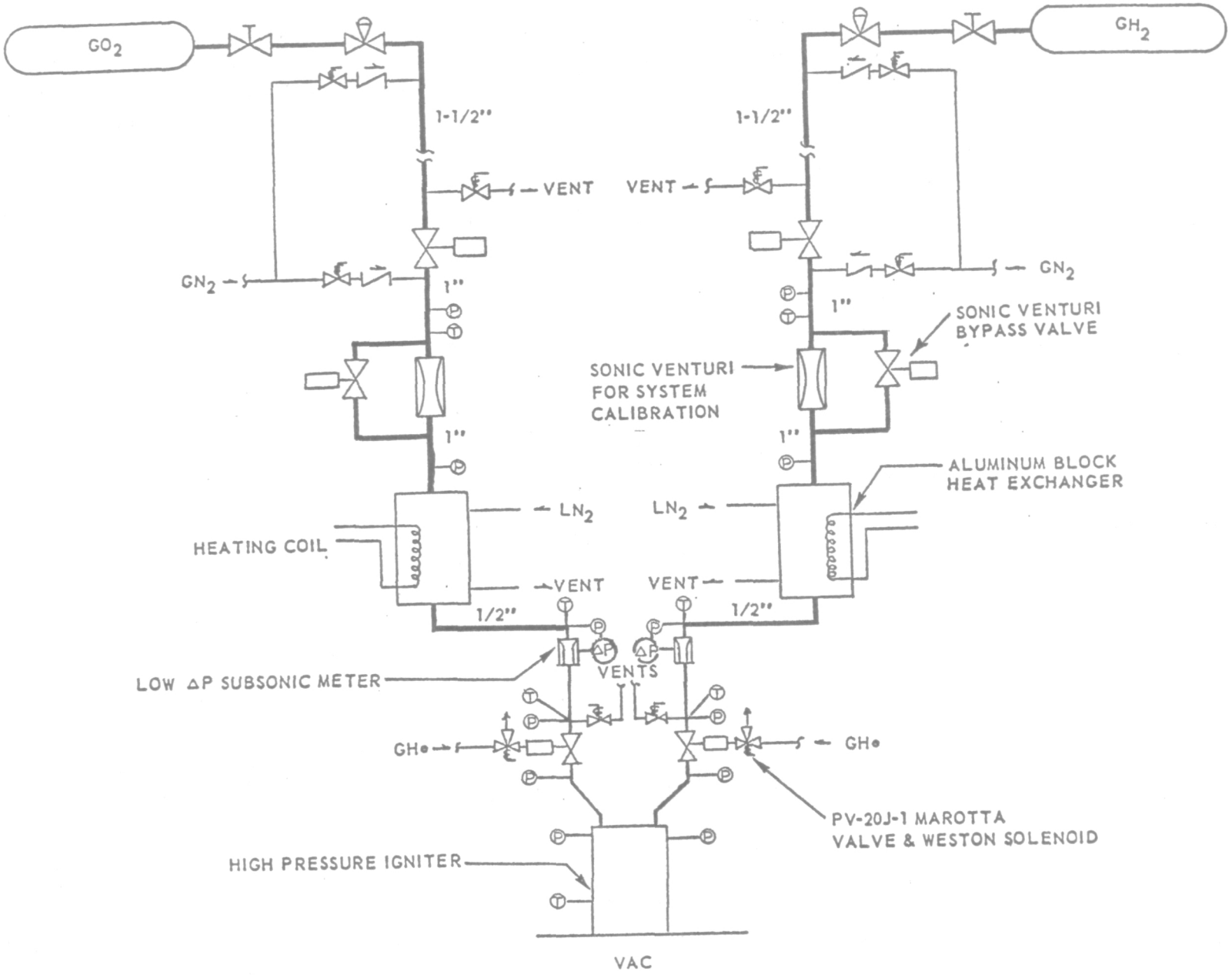


Figure 34 High Pressure Igniter Test Facility Schematic

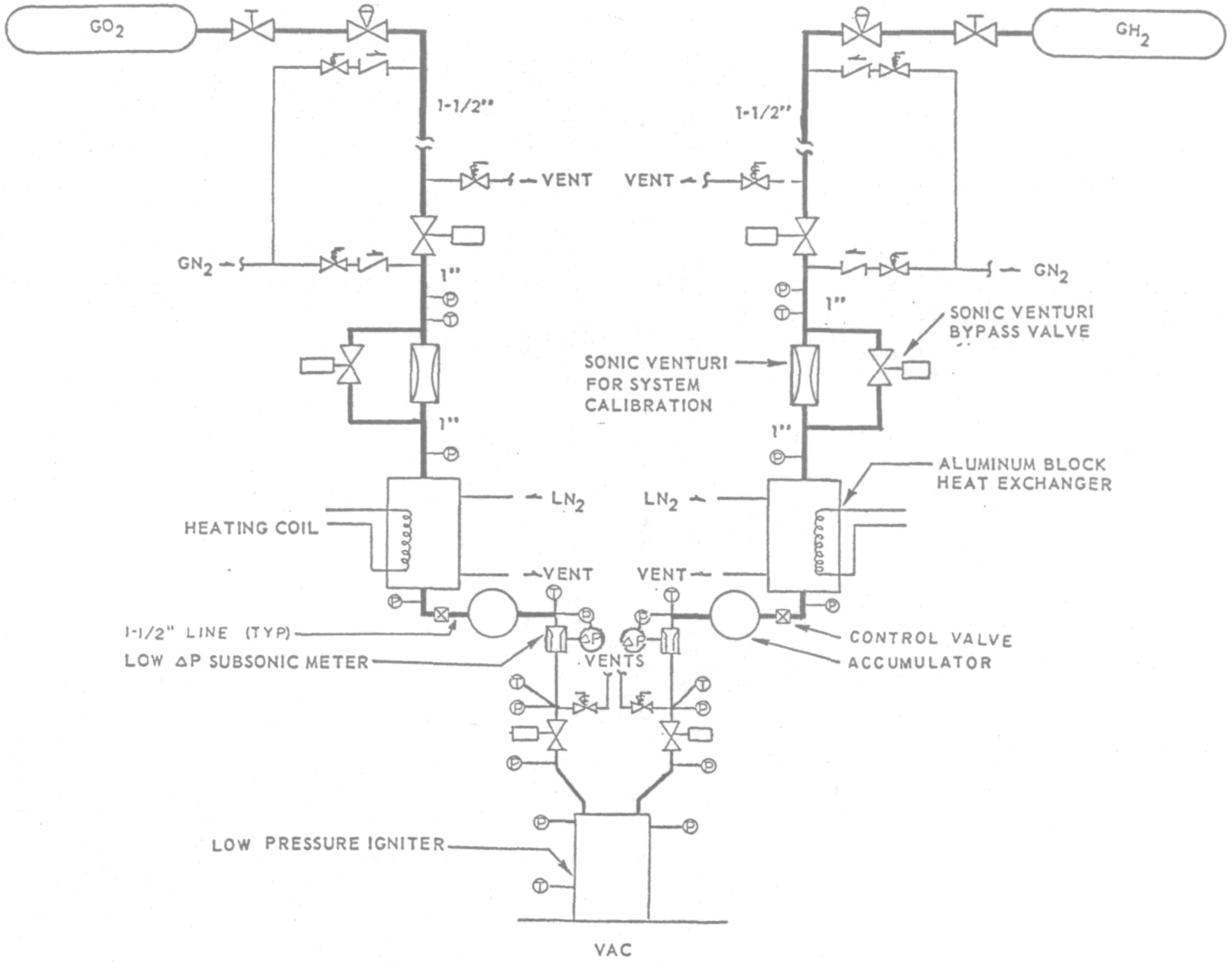


Figure 35 Low Pressure Igniter Test Facility Schematic

An aluminum heat sink exchanger is used to provide conditioned propellant to a given temperature from 200 to 800 R (111 to 444 K). The heat exchanger has a propellant coil, liquid nitrogen coil, and electric heating coil embedded within an aluminum casting. Cold temperature conditioning is achieved by flowing liquid nitrogen and using the heating coil in an on/off mode to achieve fine control of the aluminum block temperature. Hot temperature conditioning is achieved by using the heating coil only. During ambient temperature tests, the heat exchanger is bypassed to eliminate the heat exchanger pressure drop. Downstream of the heat exchanger on the high pressure system (Fig. 34) the system is close-coupled to reduce system mass and time required to temperature condition the system. Close-coupled to the igniter valves is a low pressure drop subsonic venturi to measure transient and steady-state flowrate and a bleed point to precondition the system temperature up to the valve inlet.

The low pressure system is shown in Fig. 35, and downstream of the heat exchanger is: (1) a control valve to regulate the downstream pressure to 20 psia (14 N/cm^2), (2) an accumulator to maintain constant pressure during valve sequencing and igniter operation, (3) a low pressure drop subsonic venturi to measure transient and steady-state flowrate, and (4) a bleed point to precondition the system temperature up to the valve inlet.

System Control. All tests are conducted using an automatic sequencer. The sequence includes operation of the fuel valve, oxidizer valve, fuel bleed valve, oxidizer bleed valve, and spark on/off. The sequencer is capable of controlling valve and spark signals to any specified relative position in time within 1 millisecond. Prior to each test series, the sequence is verified with the systems pressurized with GN_2.

A continuous flow of propellants at approximately the test flowrates is maintained through a vent immediately upstream of the igniter valve. In this manner, the specified propellant temperature and pressure is maintained at the valve inlet. During the test, the vent valves are sequenced closed immediately before the igniter valves are sequenced open.

Instrumentation. Sufficient pressure and temperature sensors are used to establish and monitor the system/hardware conditions. Data acquisition includes a high-speed digital system, a high-frequency oscillograph recorder and a 6-channel Brush recorder.

Hardware

The design of high and low pressure spark igniters are based upon the results of Task I analysis and cold-flow evaluation. The igniter hardware is shown in Fig. 36 and Fig. 37, while assembly sketches are shown in Fig. 38 and Fig. 39.

The igniter design approach involves providing a relatively high mixture ratio and low velocity gas mixture locally at the spark plug while maintaining overall mixture ratio of 1.0:1 (o/f). A single (self-impinging doublet) oxidizer element is placed at the head end of the igniter and all the fuel is injected tangentially through eight orifices downstream of the oxidizer. The major portion of the fuel film cools the igniter walls while a small portion of the fuel recirculates to the head end of the igniter. This provides a low velocity, high mixture ratio region at the spark plug location.

The electrical system includes the 0.025-inch (0.064 cm) dual recessed gap spark plug and variable energy inductive unit fabricated during Task I. The unit operates by storing a calibrated energy in a fixed inductor. The inductor is charged at a constant rate and the stored energy level is controlled by

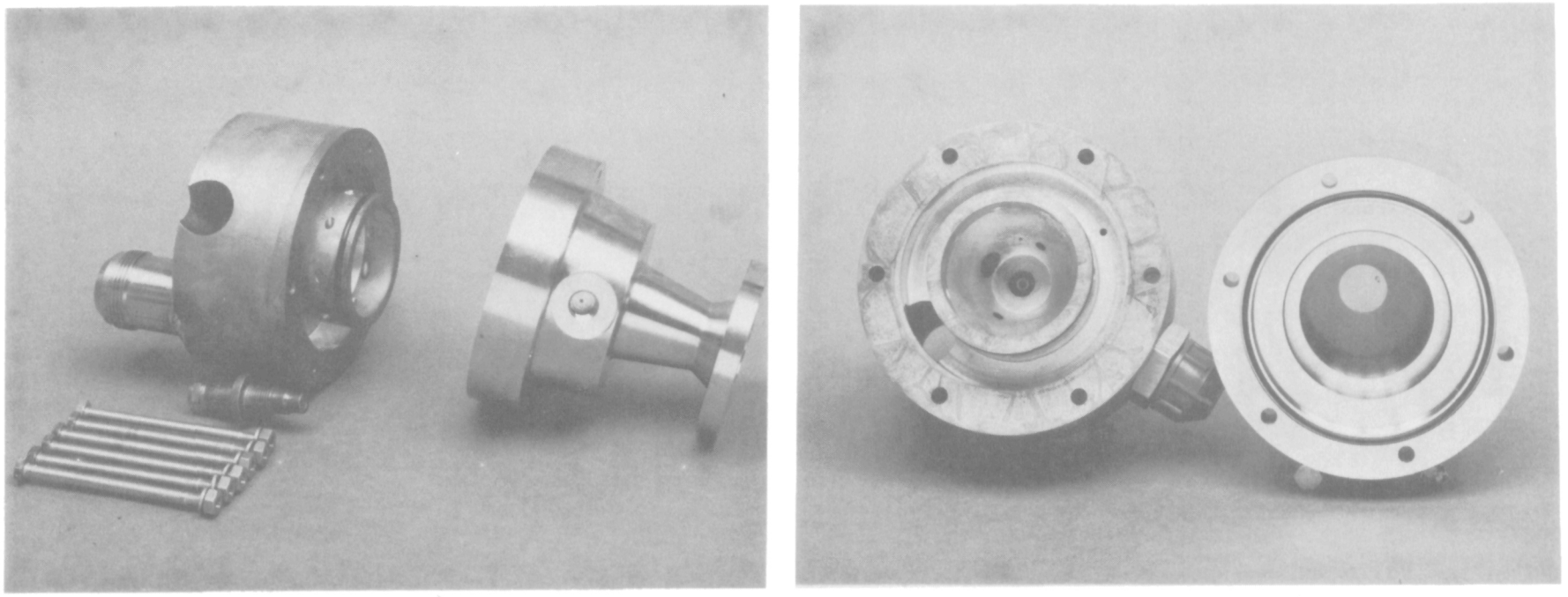


Figure 36. Low Pressure Spark Igniter

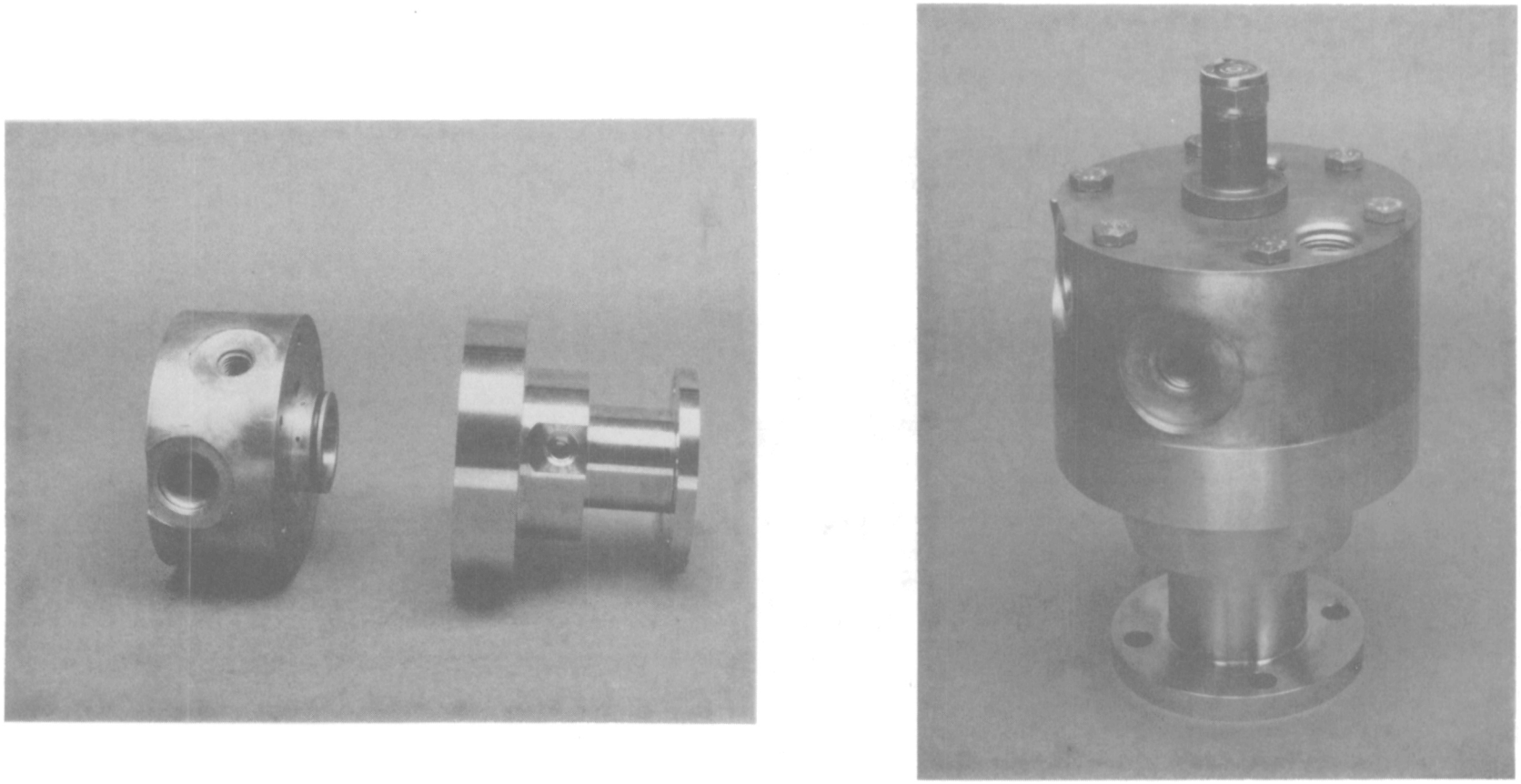


Figure 37. High Pressure Spark Igniter

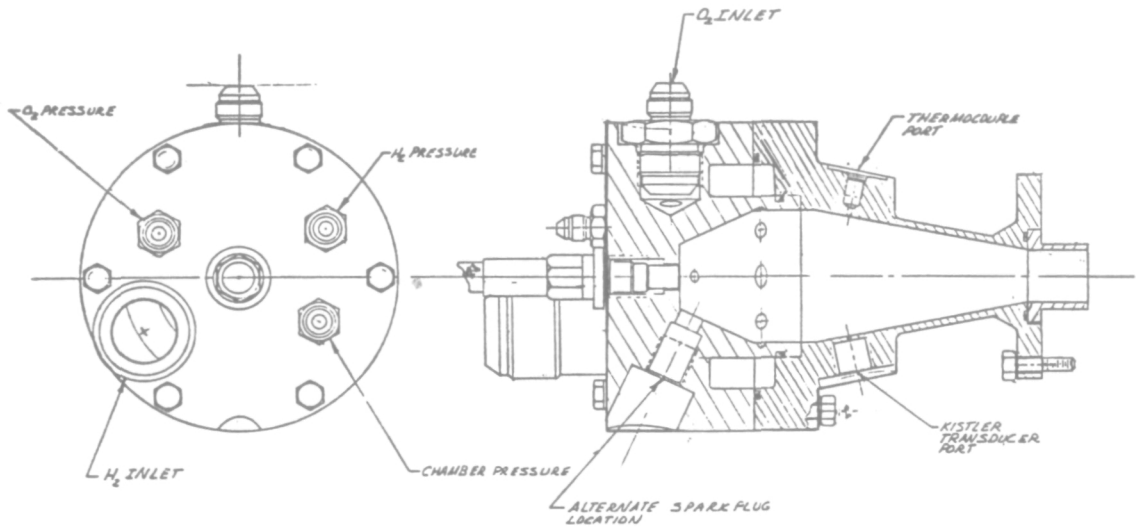


Figure 38. Low Pressure Igniter Assembly

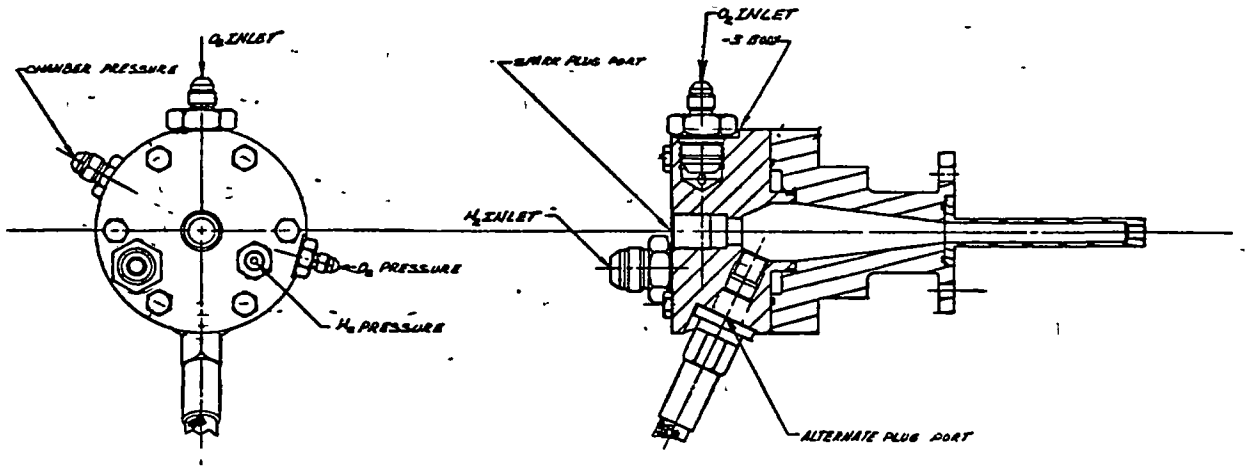


Figure 39. High Pressure Igniter Assembly

the duration of the gating interval. At the end of the storage interval, the inductor current is switched and the stored energy is discharged into a voltage step-up transformer to the spark plug gap. This operation is shown diagrammatically in Fig. 40. The inductance unit is capable of varying stored energy and spark rate. Monitor points are provided for pulse rate, energize current and output voltage and current.

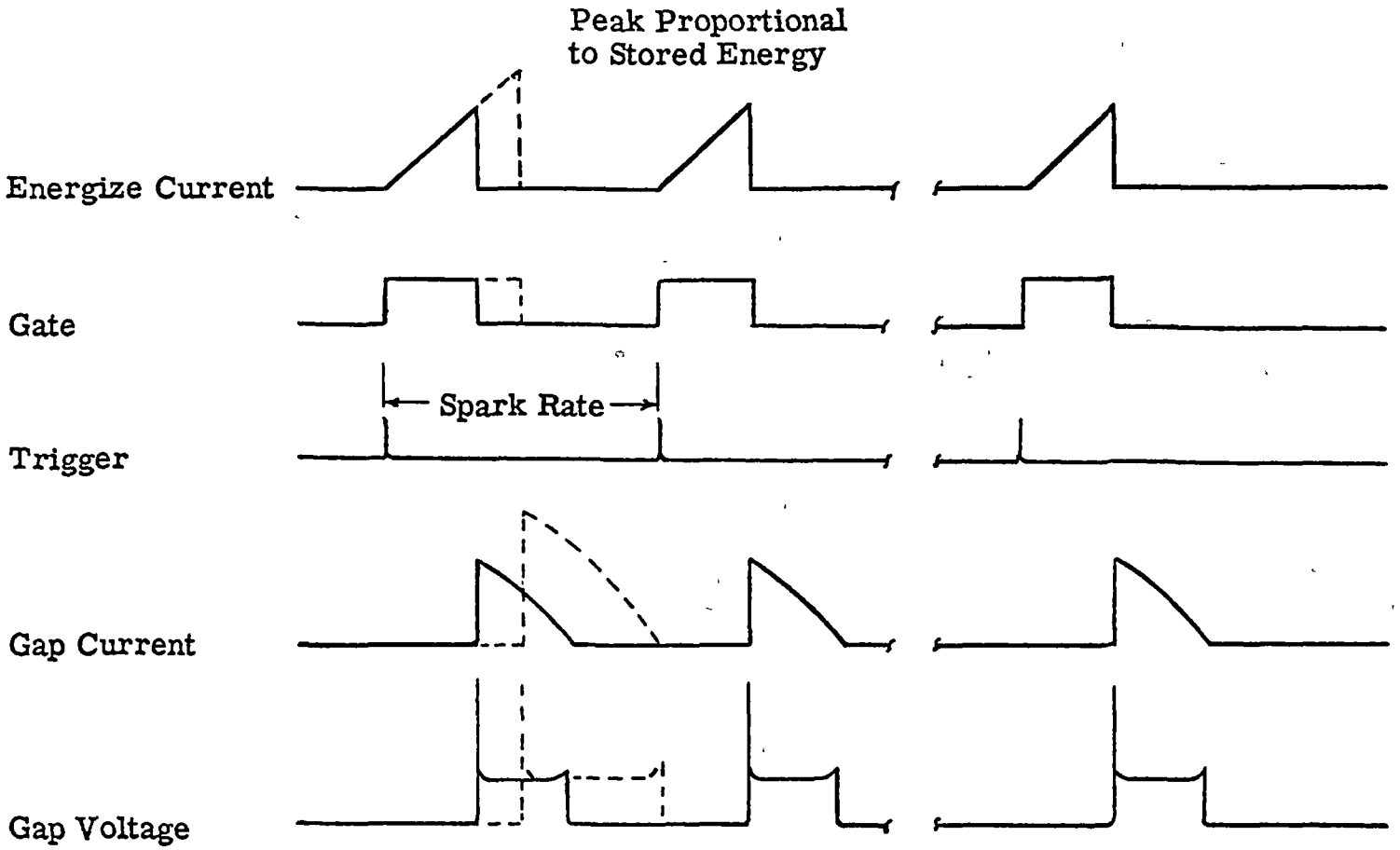
LOW PRESSURE SPARK IGNITER TEST RESULTS

Igniter only testing of the low pressure spark igniter configuration commenced on 15 December 1970 and was completed on 22 December 1970. Satisfactory operation of the igniter using inductance spark ignition was demonstrated over a range of propellant inlet conditions.

Summary

A summary of the low pressure results is presented in Table 8 . Testing consisted of: (1) igniter evaluation, (2) spark energy evaluation, (3) operational limits determination, and (4) additional tests. Results of this effort are summarized below.

Igniter Evaluation. Basic igniter operating characteristics were ascertained using a J-2 spark plug at two plug locations. Repeated ignitions were demonstrated at all mixture ratios in the range of interest and at spark energies well below the design goal of 30 millijoules stored. Ignition and sustained burning did not produce any adverse heating of the combustor. The flow was demonstrated to be highly stratified with a cool, fuel-rich flow at the walls and a hot oxidizer-rich flow in the core. Salient results were: (1) ignition delay of 10 milliseconds after inception of propellant flow, (2) no adverse heating of the combustor or spark plug, (3) ignition at all mixture ratios tested, (4) ignition at a stored spark energy of 3 millijoules (approximately



Spark Rate: Single to 1000 cps

Figure 40. Variable Energy Exciter Operation

TABLE 8

LOW PRESSURE SPARK IGNITER TEST PROGRAM SUMMARY

Test Phase	Plug Type	Variables	No. of Tests	Results
Igniter Evaluation	J-2	Plug Location (2) Energy Level (1.6 to 68 mJ)* Mixture Ratio (1.0 to 1.5 o/f)	21	Ignition Delay $\leq$ 15 ms No Heating of Igniter or Spark Plug Ignition at All Mixture Ratios Tested Ignition at Energy $\geq$ 3 mJ No Effect of Plug Location Repeated Ignitions
Spark Energy	Dual Gap Recess	Plug Location (2) Energy Level (3 to 68 mJ) Mixture Ratio (0.8 to 1.5 o/f)	26	
Operational Limits **		Spark Rate (100 to 200 cps)	4	No Effect of Rate on Ignition
		Flow Rate (0.8 to 1.25 X Nominal) Energy Level (21 mJ)	4	No Effect of $\dot{w}$ on Ignition (P_c = Const.) No Effect of P_c on Ignition ($\dot{w}$ = Const.) No Effect of $\dot{w}$ on Energy No Effect of P_c on Energy
		Throat Area (1.25 X Nominal) Flow Rate (0.8 to 1.0 X Nominal) Energy Level (7 to 68 mJ)	7	
		Temperature (200 to 800 R (111 to 444 K)) Energy Level (7 to 68 mJ)	26	No Effect of Temperature on Ignition No Effect of Temperature On Energy
Additional Tests **		Sequencing (Fuel Lead to Oxidizer Lag) Energy Level (21 to 68 mJ)	11	No Effect of Fuel Lead on Ignition Oxidizer Lag (Relative to Spark) Affected Ignition at 21 mJ *** No Effect of Sequence at 68 mJ
		Duration (1 to 11 sec)	4	No Heating of Igniter or Spark Plug at Extended Duration

* Millijoules of stored energy
** Side spark plug location
*** Result of workhorse inductance unit design

0.5 millijoules delivered), and (5) no influence of the two spark plug locations.

Spark Energy. The 0.025-inch (0.064 cm) dual recessed gap spark plug selected from Task I testing was evaluated. The selected spark plug produced the same successful results as the igniter evaluation tests using the J-2 spark plug.

Operational Limits. During this series, the igniter demonstrated satisfactory operation for variations in: (1) spark rate (100 to 200 cps), (2) flowrate (0.8 to 1.25 X Nominal), (3) throat area (1.25 X Nominal), and (4) propellant inlet temperature [200 to 800 R (111 to 444 K)]. No significant influence of these parameters upon minimum energy requirements was found.

Additional Tests. The sequencing of the fuel, oxidizer and spark was evaluated and the results demonstrated that successful operation of this spark igniter configuration does not depend upon critical sequencing.

Extended duration tests were conducted at durations of 11 seconds (nominal test duration was 1 second). There was no evidence of heating of the combustor or burning of the spark plug tip.

Test Results

During the test effort, 103 tests were conducted over a practical range of propellant inlet conditions and electrical ignition conditions. Nominal test conditions were a flowrate of 0.04 lb_m/sec (0.018 kg/sec), mixture ratio of 1.0:1 (o/f), chamber pressure of 16 psia (11.0 N/cm^2), and ambient temperature propellants. These conditions and the nominal sequence is shown in Table 9

TABLE 9

NOMINAL TEST CONDITIONS - LOW PRESSURE SPARK IGNITER

	Nominal	Variation
Chamber Pressure	16.6 psi_2 (11.5 N/cm^2)	11.9 - 20.6 $psia_2$ (8.2 - 14.2 N/cm^2)
Mixture Ratio (o/f)	1.0:1	0.8:1 - 1.7:1
Flowrate	0.04 lb_m/sec (0.018 Kg/sec)	0.05 - 0.03 lb_m/sec (0.023 - 0.014 Kg/sec)
Fuel Temperature	520 R (289 K)	241 - 776 R (134 - 431 K)
Oxidizer Temperature	520 R (289 K)	297 - 644 R (165 - 358 K)
Stored Spark Energy	21 mj	1.6 - 68 mj
Delivered Spark Energy (est.)	3 mj	0.3 - 10 mj
Sequence	Start: Fuel & Oxid. Flow, and Spark Oxid. Duration: 0.84 sec Cutoff: Fuel Lag of 0.16 sec	Start: Fuel Lead to Oxid. Lag Duration: 1.5 sec Cutoff: No Fuel Lag

The majority of tests resulted in rapid ignition with less than 3 millijoules of delivered energy. The igniter combustor characteristics, effect of propellant inlet conditions upon incident of ignition, and effect of the inductive spark discharge upon ignition were ascertained.

Combustor Characteristics. Basic combustion device flow characteristics were determined in terms of pressure and temperature distribution, igniter response, and igniter heating.

Chamber Pressure. The flow was demonstrated to be highly stratified with a cool, fuel-rich flow at the walls and a hot, oxidizer-rich flow in the core. The tangential nature of the fuel flow was revealed during blowdowns using gaseous hydrogen and nitrogen. With hydrogen only flow, the throat discharge coefficient has a value of 0.4. As axial flow (nitrogen or oxygen) is added, the discharge coefficient increases toward a value more reasonable of axial flow as shown in Fig. 41. At a mixture ratio of 1.0:1 (o/f), the un-ignited flow produces a discharge coefficient of 0.6, which is the result obtained during Task I cold flow experiments.

After ignition, the chamber pressure increases to a value which is a function of the ignited flow discharge coefficient and overall combustion performance (η_{c^*}). It is reasonable that combustion performance is well below the ideal value of unity because of the stratified flow. It is also reasonable that the discharge coefficient increases during combustion from its cold flow value due to turbulence from combustion. Figure 42 presents the extremes of these two conditions and it is not possible to separate the two effects.

Pressure Profile. Pressure profile of the low pressure igniter is presented in Table 10 for a range of inlet conditions. Most of the tests were

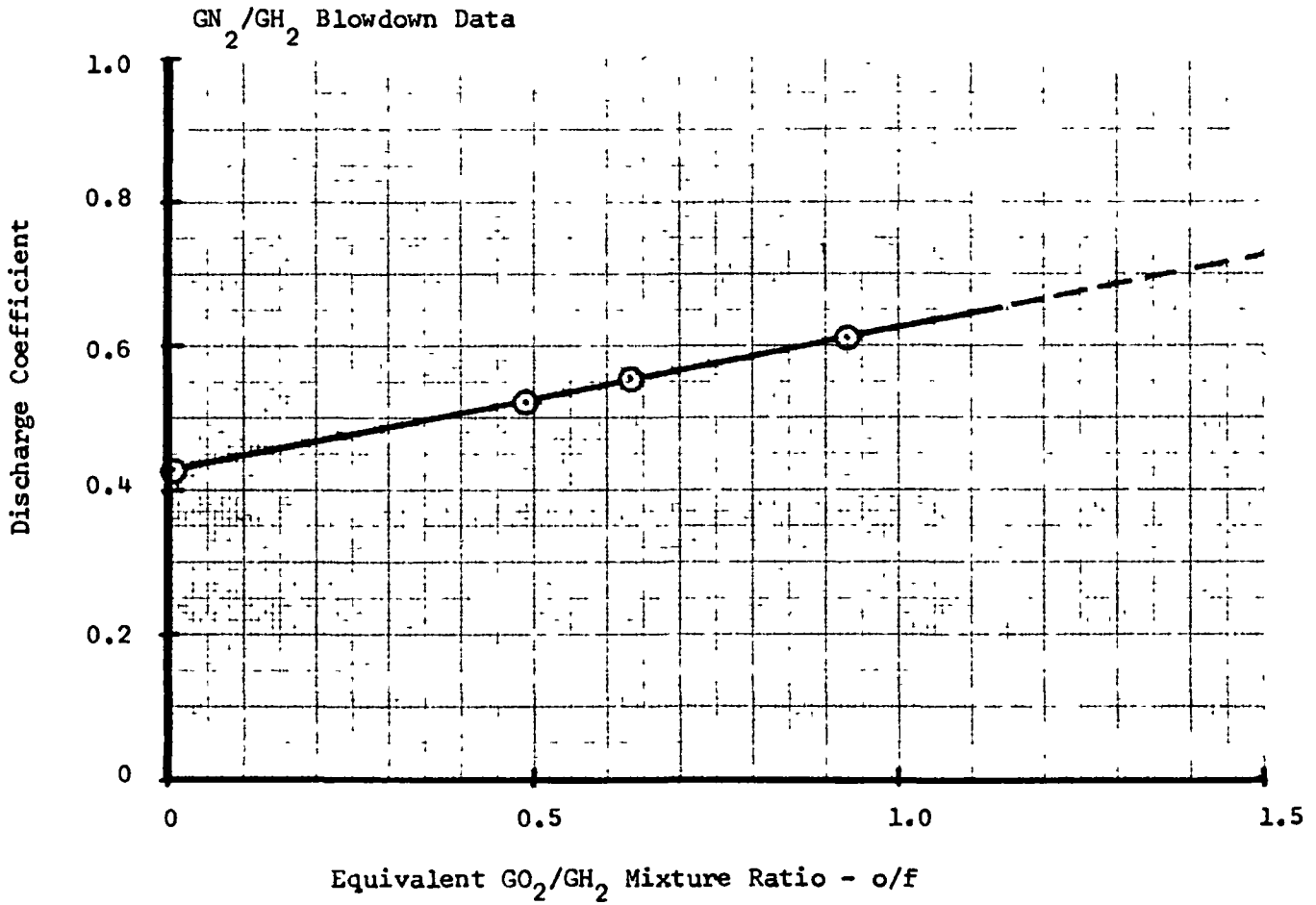


Figure 41. Un-ignited Throat Discharge Coefficient

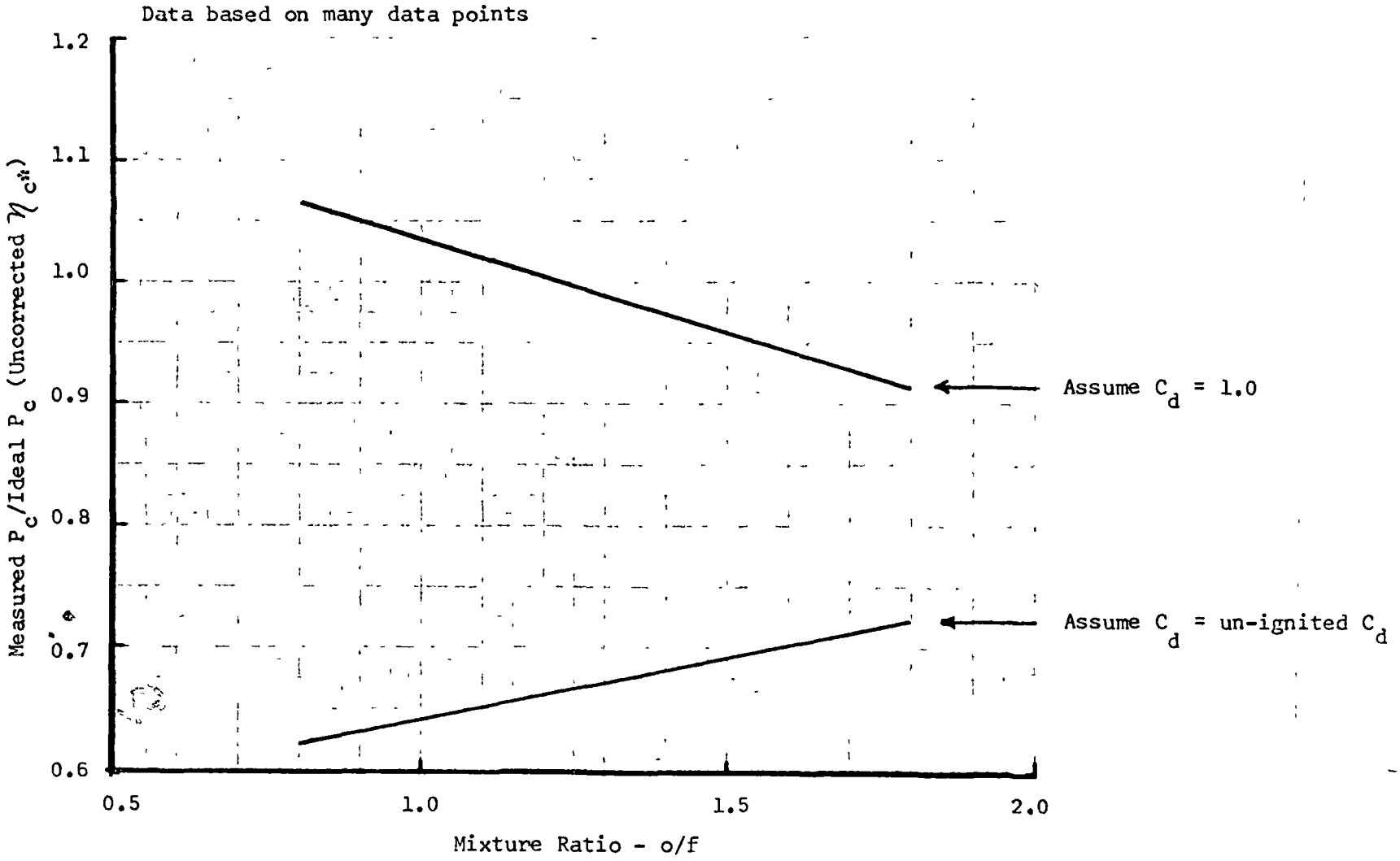


Figure 42 . Ignited Combustion Performance and Discharge Coefficient

TABLE 10

LOW PRESSURE SPARK IGNITER PRESSURE PROFILE

MR o/f	$\dot{W}$ lb_m/sec (Kg/sec)	P_c psia (N/cm^2)	Fuel		Oxidizer	
			Inj. psia (N/cm^2)	Inlet psia (N/cm^2)	Inj. psia (N/cm^2)	Inlet psia (N/cm^2)
0.8	0.04 (0.018)	16.8 (11.6)	24.7 (17.0)	25.7 (17.7)	20.0 (13.8)	22.9 (15.8)
1.0	↓	16.6 (11.4	23.0 (15.8)	23.9 (16.5)	20.7 (14.3)	27.1 (16.6)
1.5		16.0 (11.0)	20.3 (14.0)	20.9 (14.4)	22.2 (15.3)	26.8 (18.5)

520 R (289 K) Propellant Temperature.

0.242-inch (0.61 cm) Diameter Nozzle in Oxidizer Feed System.

conducted using orifices located downstream of the igniter valves to enhance facility/igniter operations and increase test frequency and flow control. A test series was conducted without any orifices and there was no significant change in igniter start transients.

Combustor Temperature. The combustor flow was stratified with cool, fuel-rich gas cooling the throat convergent section and throat while the core was oxidizer-rich. Test durations were approximately 1 second and two eleven-second tests were conducted. At the conclusion of the test series, the igniter did not show any evidence of heating of the combustor or spark plug tips.

Three temperature measurements (open tip thermocouples) were made: (1) combustion temperature probe at the convergent section, (2) spark plug tip measurement made with a "dummy" spark plug at the alternate location (selected tests), and (3) external throat temperature on the throat section to be used with the thruster injector (selected tests). Temperature results are shown in Fig.[43] for an extended duration test. These results indicate that after 11 seconds, the combustor was near temperature equilibrium and the igniter is capable of extended duration operation being cooled only by its unique internal flow characteristics.

The combustion temperature probe (convergent section) was sensitive to immersion depth. At a distance of 0.25 inch (0.6 cm), as measured from the wall surface, the temperature would typically increase by less than 100° F (56 C) and occasionally record 1500° F (815 C). This indicated the presence of a cool fuel boundary layer that was at least 0.25 inch (0.6 cm) thick. When the thermocouple immersion depth was increased to 0.5 inch (1.3 cm), the probe would burn out at ignition and burn back to a depth of 0.3 inch (0.8 cm).

Figure 43. LOW PRESSURE IGNITER TEMPERATURE

TEST NO. 103

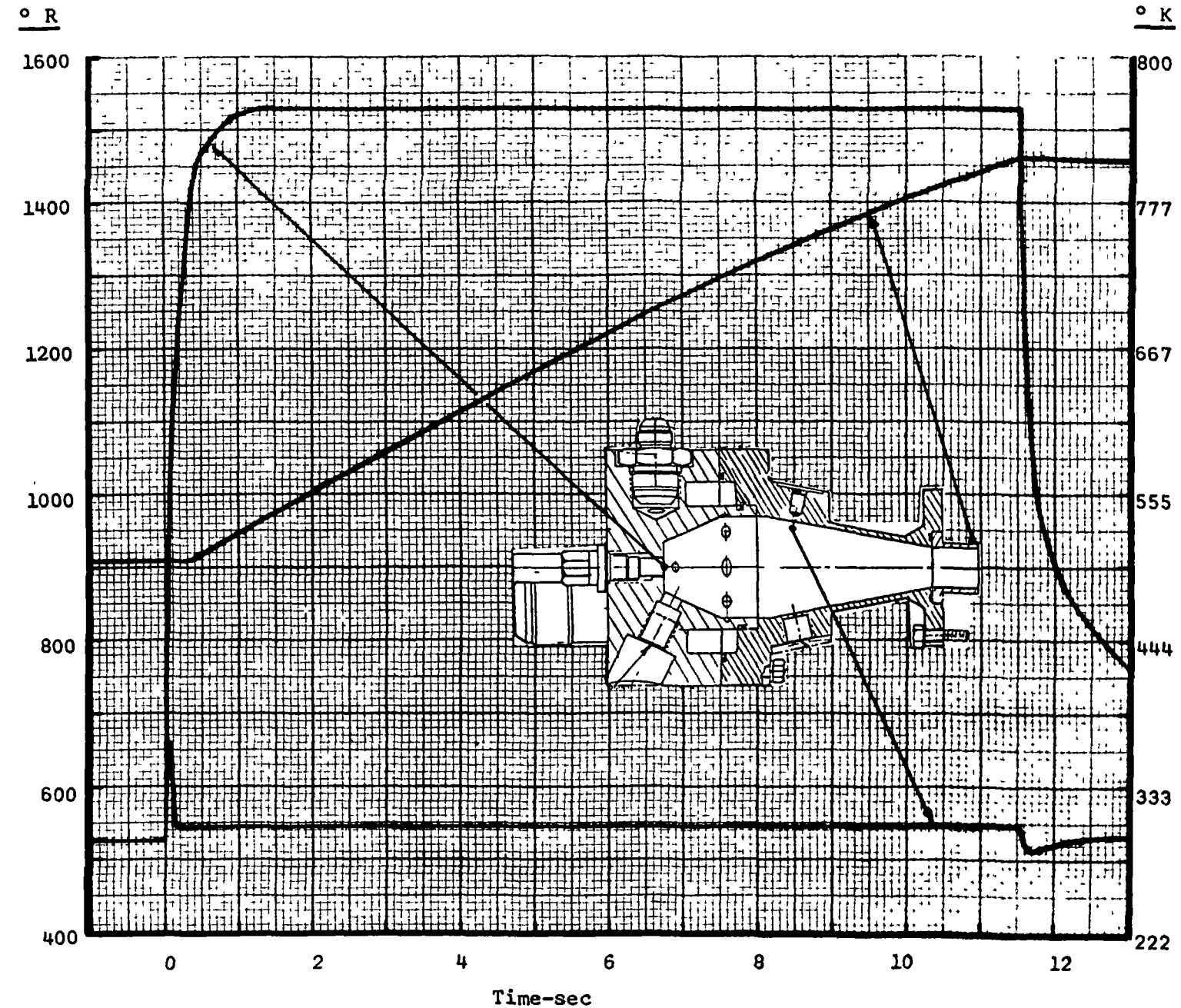
P_c = 16.4 psia (11.3 N/cm^2)

$\dot{W}_T$ = 0.036 lb_m/sec (0.016 Kg/sec)

MR = 1.14 O/f

Duration = 11.5 sec

Ambient Temperature Propellants



This further verified the presence of a fuel boundary layer to approximately 0.3 inch (0.8 cm) and a high temperature core.

Igniter Response. Typical igniter response is shown by the oscillograph trace in Fig. 44. Ignition occurred on the third spark 8 milliseconds (ignition delay) after inception of the propellant flow and 44 milliseconds after valve electrical signal. Pressure response measured to 90 percent of ignited chamber pressure was 49 milliseconds after electrical start. Propellant inlet conditions, such as inlet pressure, propellant temperature, flowrate and mixture ratio,did not have a significant effect on ignition delay or pressure response.

Inlet Conditions. The effect of propellant inlet conditions on ignition was investigated for variations in mixture ratio, flowrates, chamber pressure, and propellant temperatures.

Mixture Ratio. Mixture ratio was varied from 0.8:1 to 1.7:1 (o/f) while stored energy was varied down to 1.6 millijoules. There was no influence of mixture ratio on ignition, ignition delay, or minimum required spark energy. These tests are summarized in Table 11. All mixture ratios resulted in ignition for a stored energy of 3 millijoules or greater (approximately 0.5 millijoules delivered spark energy).

Flowrate and Chamber Pressure. The flowrate was varied from the nominal (0.75 to 1.25 X Nominal) with a proportional change in chamber pressure. The throat area was increased (1.25 X Nominal), and the flowrate was again varied (0.75 to 1.0 X Nominal). All tests resulted in ignition with spark energy at or below the design goal of 30 millijoules stored. These results are presented in Table 12.

LOW PRESSURE IGNITER RESPONSE

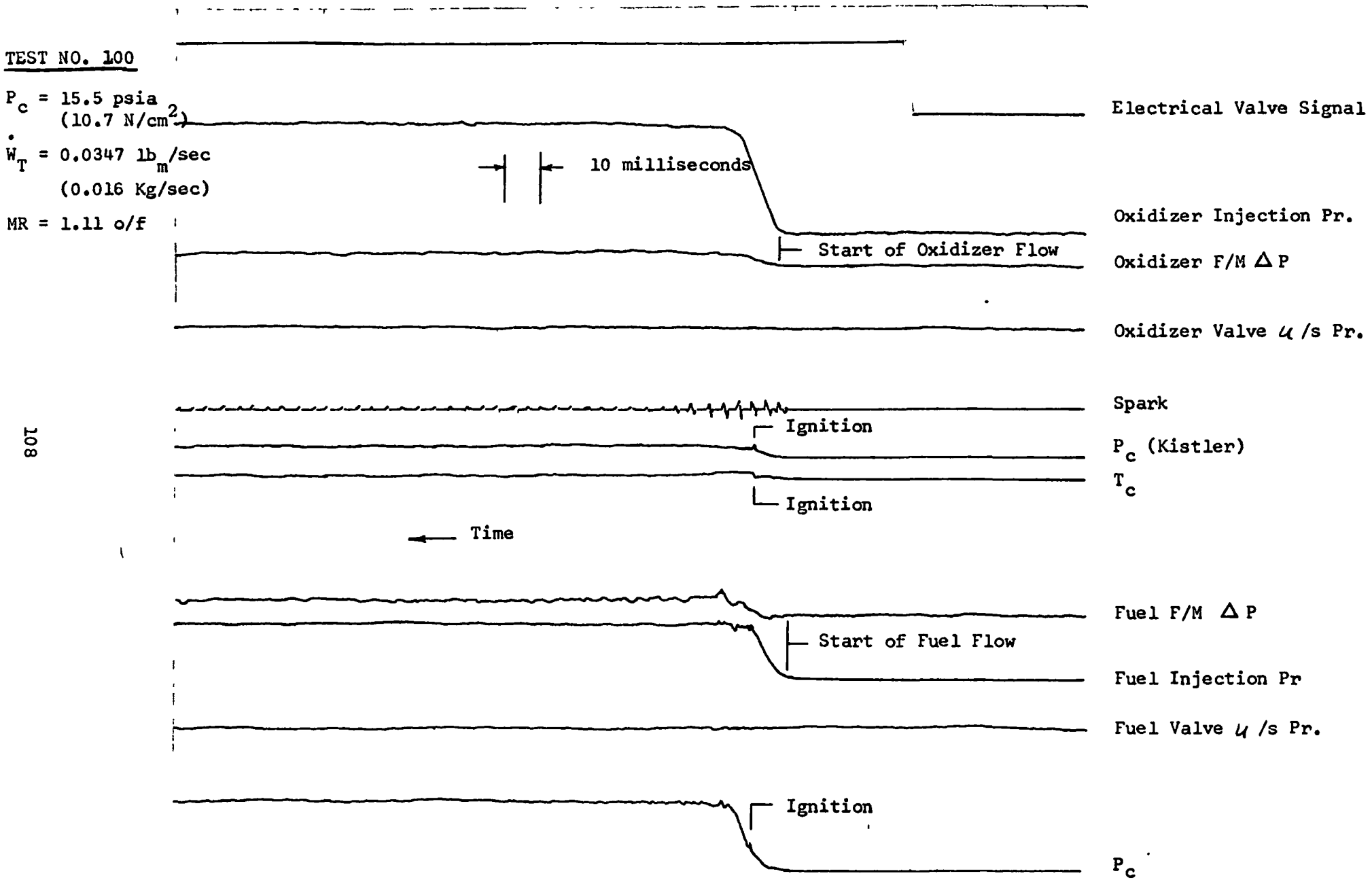


Figure 44

TABLE 11

LOW PRESSURE SPARK IGNITER
EFFECT OF MIXTURE RATIO VARIATION

Test Phase	Spark Plug	Loc.	MR	P_c psia	P_c N/cm^2	$\dot{W}_T$ lb_m/sec	$\dot{W}_T$ Kg/sec	Energy-mj Stored	Energy-mj Del.	No. of Tests	No. of Ign.
Igniter Evaluation	J-2	Ctr.	1.09	16.3	11.2	.0392	.0178	3.1-68	0.5-10	8	8
	"	"	1.46	16.5	11.4	.0398	.0181	7.5	1.1	1	1
"	"	"	1.71	16.2	11.2	.0403	.0189	3.1-7.5	0.5-1.1	4	4
"	"	"	1.49*	9.7*	6.7	.0421*	.0191	1.6	0.2	2	0
"	"	Side	1.05	16.0	11.0	.0387	.0176	3.1-68	0.5-10	4	4
"	"	"	1.65	15.8	11.6	.0400	.0182	3.1	0.5	2	2
Spark Energy	Dual Gap	Ctr.	1.05	15.9	10.9	.0381	.0173	3.1-68	0.5-10	4	4
"	Recess	"	0.83	15.2	10.5	.0361	.0164	3.1	0.5	2	2
"	"	"	1.63	N.G.	-	.0399	.0181	3.1	0.5	1	1
"	"	Side	1.10	16.7	11.5	.0373	.0169	7.5-68	1.1-10	9	9
"	"	"	1.13	16.5	11.4	.0379	.0172	3.1	0.5	3	2
"	"	"	0.92	16.2	11.2	.0387	.0176	7.5	1.1	2	2
"	"	"	1.76	16.1	11.1	.0408	.0185	7.5	1.1	2	2

Average Values of P_c, $\dot{W}_T$, and MR

* Un-ignited condition

Ambient temperature propellants

TABLE 12

LOW PRESSURE SPARK IGNITER
EFFECT OF FLOWRATE & THROAT AREA

Test Phase	Throat Diameter in.	Throat Diameter cm	MR	P_c psia	P_c N/cm^2	$\dot{W}_T$ lb_m/sec	$\dot{W}_T$ Kg/sec	Energy-mj Stored	Energy-mj Del.	No. of Tests	No. of Ign.
Spark Energy	0.882	2.24	1.10	16.7	11.5	.0373	.0169	7.5-68	1.1-10	9	9
Operational Limits	"	"	1.19	20.3	14.0	.0491	.0223	21	3.2	2	2
"	"	"	1.19	12.0	8.3	.0300	.0136	21	3.2	2	2
"	0.799	2.03	1.10	19.6	13.5	.0392	.0178	7.5-68	1.1-10	4	4
"	"	"	1.16	16.2	11.2	.0332	.0151	7.5	1.1	3	3

Dual gap recess spark plug at side location.

Average values of P_c, $\dot{W}_T$, and MR.

Ambient temperature propellants.

Propellant Temperature. Propellant temperature was varied over the range of 200 to 800 R (111 to 444 K) at a mixture ratio of 1.0:1 (o/f) and spark storage energies of 20 millijoules or less. All tests resulted in ignitions with ignition delays of less than 15 milliseconds. These results are presented in Table 13.

Sequencing. In the nominal sequence, both propellant flows and the first spark occurred at the same time (± 2 milliseconds). To investigate the sensitivity of the igniter to sequencing, the fuel flow was started 40 milliseconds early. Ignition occurred at 10 milliseconds after start of oxidizer flow which was the same ignition delay as the nominal sequence.

Oxidizer flow was delayed relative to the spark and fuel flow. At 21 millijoules, appreciable ignition delays and ignition failures occurred. These failures were a result of a defect in the workhorse exciter unit in which the stored spark energy diminished with succeeding sparks. At 68 millijoules of stored energy, all tests were ignitions with minimal ignition delays. (As explained in the next section, the variable energy exciter due to its low efficiency delivered approximately 15 percent of the stored energy, i.e., 10 millijoules delivered for 68 millijoules stored.)

Spark Ignition System. The effect of spark ignition system on ignition was investigated for variations in spark energy and spark plug location. The spark plug selected from Task I testing was the 0.025-inch (0.064 cm) dual recess gap plug. A variable energy exciter fabricated during Task I was used to provide the inductive spark energy.

TABLE 13

LOW PRESSURE SPARK IGNITER
EFFECT OF PROPELLANT TEMPERATURE

Test Phase	MR	P_c psia	P_c N/cm^2	$\dot{W}_T$ lb_m/sec	$\dot{W}_T$ Kg/sec	Fuel Temp. R	Fuel Temp. K	Oxid. Temp. R	Oxid. Temp. K	Energy mj Stored	Energy mj Delivered	No. of Tests	No. of Ign.
Spark Energy	1.10	16.7	11.5	.0373	.0169	520	289	516	287	7.5-68	1.1-10	9	9
Operating Limits	1.17	17.8	12.3	.0425	.0193	650	361	642	357	7.5-21	1.1-3.2	3	3
"	1.14	17.3	11.9	.0407	.0185	775	431	635	353	7.5	1.1	3	3
"	1.07	15.2	10.5	.0345	.0157	354	197	354	197	7.5-68	1.1-10	4	4
"	0.86	13.8	9.5	.0319	.0145	356	198	342	190	7.5	1.1	2	2
"	1.30	16.3	11.2	.0377	.0171	362	201	338	188	7.5	1.1	2	2
"	1.20	13.9	9.6	.0338	.0153	252	140	316	176	7.5-21	1.1-3.2	3	3

Average values of P_c, $\hat{W}_T$, MR, and temperature.

Inductance Unit Operation. The workhorse inductive exciter unit was capable of varying stored energy and spark rate. During Task I laboratory testing, the usual mode of operation was a single spark. A predetermined stored spark energy could be obtained by a calibrated dial setting.

The exciter unit had a defect when used in the multiple spark mode. The first spark contained the preselected stored energy, but the energy diminished with succeeding sparks as shown in Fig. 45. This was due to a transformer which was manufactured out of specification and would quickly saturate during the multiple spark mode.

Under hot-firing conditions with the nominal test sequence, the spark energy would diminish as the igniter pressure was rising. At low energy levels, sparking would cease after the fourth to fifth spark. This was not a significant factor during the low pressure igniter test effort since ignition usually occurred on the second to fourth spark.

Spark Energy. A test series was conducted to determine the delivered spark energy under hot-fire conditions. A high response F/M tape unit was used to monitor the output voltage, current, and trigger current as well as critical igniter pressures. The igniter was operated at nominal test conditions and the results are presented in Table 14. Proper conditions for ignition such as mixture ratio and pressure occurred at the second to third spark. Ignition was achieved at a minimum delivered energy of 0.4 millijoules. There was an ignition failure at a delivered energy of 0.4 millijoules; however, proper conditions may not have been obtained by the third spark. This indicates a marginal energy level for ignition.

INDUCTANCE EXCITER DELIVERED ENERGY EFFICIENCY

LOW PRESSURE IGNITER TESTS

Based on GN_2 laboratory multiple spark tests.

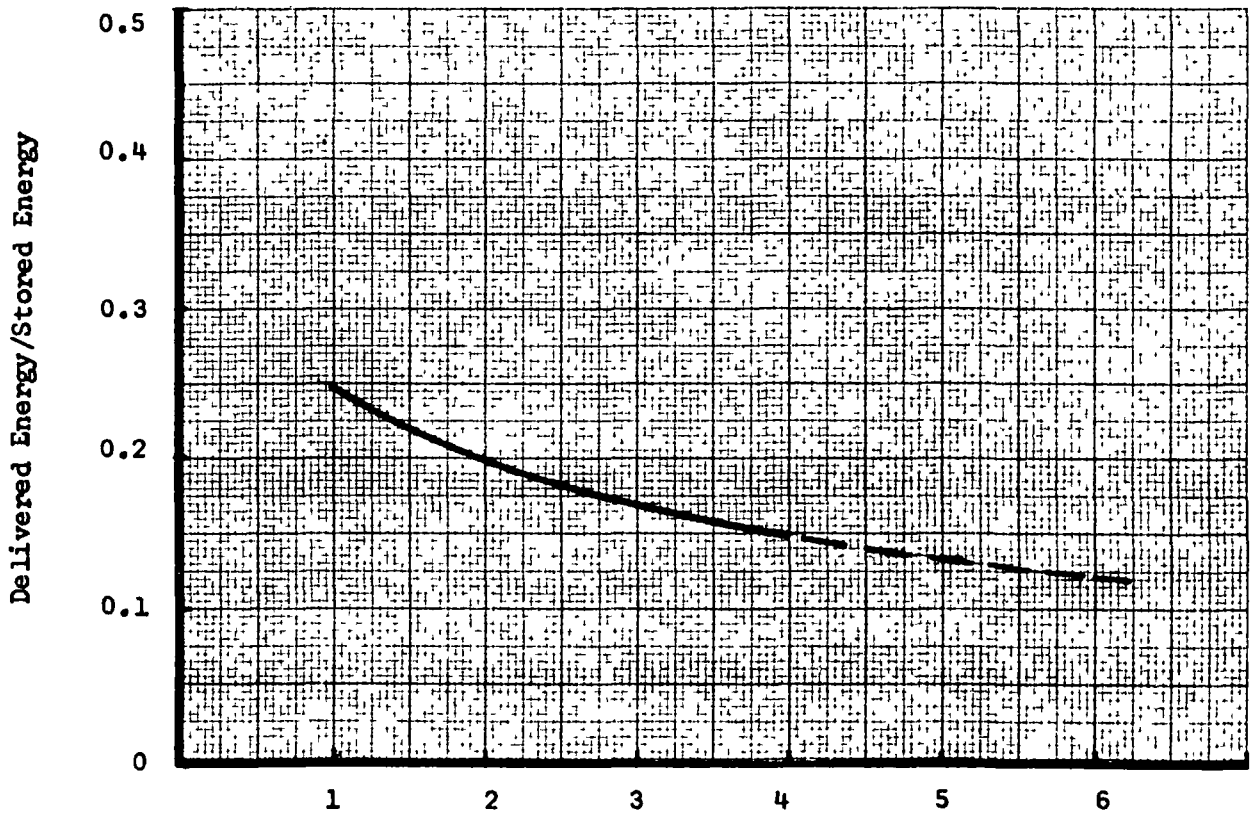


Figure 45

TABLE 14

LOW PRESSURE SPARK IGNITER
DELIVERED SPARK ENERGY

Test No.	P_c psia	P_c N/cm^2	Flowrate lb_m/sec	Flowrate Kg/sec	MR o/f	Spark Energy * Stored mj	Spark Energy * Deliv.** mj	Eff.	Ign. on Spark No.	Comments
92	16.9	11.7	.0363	.0165	1.11	22	2.6	0.12	3	
93	17.0	11.7	.0366	.0166	1.11	22	3.7	0.17	2	
94	17.0	11.7	.0360	.0163	1.10	7.5	1.6	0.21	3	
95	17.1	11.8	.0365	.0166	1.10	7.5	1.1	0.15	3	
96	12.5	8.6	.0387	.0176	1.09	3.1	0.4	0.13	-	(No ignition. Data on spark #3
97	17.0	11.7	.0367	.0167	1.11	3.1	0.4	0.13	3	(No spark after #3)
98	16.9	11.7	.0365	.0166	1.09	68	9.1	0.13	2	
99	16.9	11.7	.0359	.0163	1.05	68	9.1	0.13	2	

Average fuel inlet temperature of 530 R (294 K).
Average oxidizer inlet temperatures of 516 R (287 K).
* Energy of spark where ignition occurred
** Delivered spark energy determined from F/M tape.

During the test series, most tests were conducted at stored energy levels of 20 to 70 millijoules, and ignition occurred on the second to fourth spark. In this range of operation, the exciter delivered approximately 15 percent of stored energy and reliable ignition was achieved with approximately 3 millijoules of energy. Since the integrated spark plug/exciter unit will have a greater efficiency (~75%), it appears that the design goal of 30 millijoules stored energy will have an ample margin to assure ignition.

Spark Plug Type. Two spark plugs were used on the low pressure igniter. A J-2 plug was used for initial igniter evaluation testing and the 0.025-inch (0.064 cm) dual recess gap spark plug selected from Task I evaluation was used for subsequent spark evaluation and operational limits tests. Both spark plugs performed equally well.

Spark Rate. The spark rate was varied from 200, 150 to 100 cps with nominal test conditions and sequence. There was no influence of spark rate on ignition and ignition was achieved on the spark (usually second), which occurred between 8 and 15 milliseconds after start of propellant flow.

Spark Plug Location. The igniter had the option of two plug locations which were the top of the oxidizer dome and the side of the oxidizer dome. The same ignition results occurred using both locations.

HIGH PRESSURE SPARK IGNITER TEST RESULTS

Igniter only testing of the high pressure spark igniter configuration commenced on 30 December 1970 and was completed on 21 January 1971. Satisfactory operation of the igniter using inductive spark ignition was demonstrated over a range of propellant inlet conditions.

Summary

A summary of the high pressure results is presented in Table 15. The first phase of testing was an ignition system checkout and this test effort was required to resolve deficiencies in the workhorse inductive unit. The industive unit was modified, and tne high pressure igniter testing was conducted as planned. This testing consisted of: (1) igniter evaluation, (2) spark energy evaluation, and (3) operational limits determination.

Ignition System Checkout. During the initial testing, the igniter failed to ignite. There were two unknown areas associated with this ignition system configuration: (1) the high pressure igniter had never been tested and (2) the variable energy exciter had not been used for high pressure ignition. To isolate the two possible causes, a test series was conducted where the inductive exciter was replaced by a J-2 variable energy spark (capacitance) console capable of high voltage (25 KV) and high stored spark energy (3 joules). Salient results were: (1) satisfactory combustion operation was demonstrated and (2) a minimum voltage of 20 KV was required for reliable ignition. The inductive unit had been used at 10 KV maximum voltage. Additional tests with this unit indicated that at the higher voltage settings (up to 50 KV) efficiency decreased well below 5 percent, such that sufficient spark energy to cause discharge was not produced. This unit was modified as previously described and used for subsequent testing.

Igniter Evaluation. Basic igniter operating characteristics were ascertained during this and the previous test series using a J-2 spark plug at two plug locations. Repeated ignitions were demonstrated at all mixture ratios in the range of interest and at spark energies at or below the design goal of the integrated spark/exciter unit. Ignition and sustained burning did not produce

HIGH PRESSURE SPARK IGNITER TEST PROGRAM SUMMARY
Table 15

TEST PHASE	PLUG TYPE	VARIABLES **	NO. OF TESTS	RESULTS
Ignition System Checkout	J-2 and Dual Recess Gap	Plug Location (2) Energy Level (60-3000 mj)* Mixture Ratio (0.8 to 1.5 o/f) Exciter Unit (2)	58	Igniter Combustion Characteristics Exciter Unit Limitations Defined No Heating of Igniter or Spark Plug Effect of Plug Location
Igniter Evaluation	J-2	Plug Location (1) Energy Level (12-43 mj) Mixture Ratio (0.8 to 1.5 o/f)	22	Ignition Delay $\leq$ 15 ms Ignition at All Mixture Ratio Ignition at Energy $\geq$ 12 mj Center Spark Location Selected Repeated Ignitions
Spark Energy	Dual Recess Gap	Plug Location (2) Energy Level (0.7 to 19 mj) Mixture Ratio (0.8 to 1.5 o/f)	35	
Operational Limits		Spark Rate (100 to 200 cps)	9	No Effect of Rate on Ignition
		Flowrate (0.5 to 1.0 Nominal) Energy Level (2 to 19 mj)	8	No Effect of $\dot{W}$ on Ignition (P_c = const.) No Effect of P_c on Ignition ($\dot{W}$ = const.) No Effect of $\dot{W}$ on Energy (P_c = const.) P_c Effects Required Energy
		Throat Area (2.0 x Nominal) Flowrate (1.0 to 1.5 X Nominal) Plug Location (2) Energy Level (0.1 to 14 mj)	24	
		Temperature (200 to 800 R (111 to 444 K) Energy (0.1 to 38 mj)	38	No Effect of Temperature on Ignition Apparent Effect of Temperature on Energy

* Millijoules of stored energy
** Millijoules of delivered energy unless otherwise noted

any adverse heating of the combustor. The flow was demonstrated to be highly stratified with a cool, fuel-rich flow at the outer walls and a hot, oxidizer-rich flow in the core. Salient results were: (1) ignition delays of less than 15 milliseconds after inception of oxidizer propellant flow, (2) no adverse heating of the combustor or spark plug, (3) ignition at all mixture ratios tested, (4) repeated ignition at spark energies of approximately 19 millijoules delivered, and (6) selection of the center spark plug location.

Spark Energy. The 0.025-inch (0.064 cm) dual recess gap spark plug from Task I testing was evaluated. The selected spark plug produced the same successful results as the igniter evaluation tests using the J-2 spark plug. Ignitions were obtained with as low as 1 millijoule of delivered energy.

Operational Limits. During this series, the igniter demonstrated satisfactory operation for variations in: (1) spark rate (100 to 200 cps), (2) flowrate (0.5 to 1.5 X Nominal), (3) throat area (2 X Nominal), and (4) propellant inlet temperature [200 to 800 R (111 to 444 K)]. No significant influence of these parameters upon minimum energy requirements was found with one exception. Lower chamber pressures required lower spark energies for repeatable ignitions.

Test Results

During the test effort, 136 tests were conducted over a practical range of propellant inlet conditions and electrical ignition conditions. An additional 58 tests were conducted during initial checkout testing. Nominal test conditions were a flowrate of 0.04 lb_m/sec (0.018 kg/sec), mixture ratio of 1.0:1 (o/f), chamber pressure of 230 psia (159 N/cm^2), and ambient temperature propellants. These conditions and the nominal sequence is shown in Table . The nominal chamber pressure was reduced to 120 psia (83 N/cm^2) during the

NOMINAL TEST CONDITIONS - HIGH PRESSURE SPARK IGNITER

TABLE 16

	NOMINAL	VARIATION
Chamber Pressure	230 psia ($159\ N/cm^2$)	110 to 240 psia (76 to $165\ N/cm^2$)
Mixture Ratio	1.0:1	0.8:1 to 1.5:1
Flowrate	0.04 lb_m/sec (0.018 Kg/sec)	0.021 to 0.060 lb_m/sec (0.010 to 0.027 Kg/sec)
Fuel Temperature	520 R (289 K)	212 to 783 R (118 to 435 K)
Oxidizer Temperature	520 R (289 K)	348 to 641 R (193 to 355 K)
Stored Spark Energy (Inductance)	-	2 to 210 mj
Delivered Spark Energy (est.)	-	0.1 to 43
Sequence	Start: Fuel and Spark On Oxidizer: 10 ms Lag on Start Oxid. Duration: 0.94 sec Cutoff: 60 ms Fuel Lag	Oxidizer: 0 to 20 ms Lag On Start

operational limits phase to reduce the integrated spark/exciter design requirements (lower voltage). The igniter combustor characteristics, effect of propellant inlet conditions upon incident of ignition, and effect of the inductance spark exciter upon ignition was ascertained.

A primary goal was to determine the ignitability of the system for various delivered spark energies. Measuring the delivered energy during ignition testing was difficult. At the conclusion of this report period, the maximum delivered energy for a given stored energy was determined by a special test series described in a prior section of this report.

Combustor Characteristics. Basic combustion device flow characteristics were determined in terms of feed system effects, sequencing, pressure and temperature distribution, and igniter response.

Spark Ignition Discussion. A necessary condition for successful spark ignition is that an ignitable gas mixture must be provided at the spark location. The most favorable configuration would be an igniter capable of providing an ignitable mixture during both transient and steady-state flow conditions. Consider an igniter with the fuel and oxidizer valve and spark signaled simultaneously, and a continuous spark of 200 cps. The start conditions will be dictated by the feed system. If fuel initially primes the igniter chamber, a delay will occur before the local spark mixture ratio shifts toward an ignitable mixture ratio and ignition occurs. If a balanced feed volume ratio is used, such that both propellants prime the chamber at the steady-state mixture ratio, then ignition will occur during the initial start transient. For a mixture ratio of 1.0:1 (o/f) and approximately equal inlet pressures, the required feed volume is 16:1 (fuel/oxidizer volume).

Feed Volume. The feed volume ratio used during the initial checkout testing was 9.4:1 (V_f/V_o). Ignition delay (measured from start of oxidizer flow) varied from 35 milliseconds at high energy levels to greater than 100 milliseconds at low energy levels. A balanced feed volume ratio of 16:1 (V_f/V_o) was incorporated for the planned test series and a significant decrease in ignition delay was achieved due to this change.

Valve Sequencing. The desired start sequence for the high pressure spark igniter is simultaneous fuel and oxidizer valve and spark on signal. This sequence results in simultaneous propellant flow and sparking. During the initial checkout test series, this sequence was used and several incidences of auto-ignition occurred. The occurrence of auto-ignition was verified by conducting several successful ignition tests without a spark.

Auto-ignition has been observed many times on past igniter programs using valves and a feed system similar to the high pressure spark igniter system. The phenomenon is a form of compression ignition of gaseous oxygen/hydrogen propellants, and it is currently being investigated under Rocketdyne IR&D effort. It has been observed to occur when both propellants start to flow simultaneously or when an oxidizer propellant lead is used. Ignition is immediate. The phenomenon does not occur with a fuel lead.

While auto-ignition is a phenomenon worthy of further investigation, the objective of this test series was spark ignition and repeated auto-ignitions hindered the spark ignition experimental investigation. An intentional fuel lead of 8 to 16 milliseconds was used throughout the remaining test program. This fuel lead caused the local spark plug mixture ratio to experience a fuel-rich transient before an ignitable mixture occurred at the spark location.

Chamber Pressure. The flow was demonstrated to be highly stratified with a cool, fuel-rich flow at the walls and a hot, oxidizer-rich flow in the core. The tangential nature of the fuel flow was revealed during propellant blowdowns. With hydrogen flow, the throat discharge coefficient has a value of 0.4. As axial flow (oxygen) is added, the discharge coefficient increases toward a value more reasonable for axial flow. With oxygen only, the discharge coefficient is approximately 0.97. At a mixture ratio of 1.0:1 (o/f), the un-ignited flow produces a discharge coefficient of 0.6 which is the result obtained during Task I cold flow experiments.

After ignition, the chamber pressure increases to a value which is a function of the ignited flow discharge coefficient and overall combustion performance (η_{c^*}). It is reasonable that combustion performance is well below the ideal value of unity because of the stratified flow. It is also reasonable that the discharge coefficient increases during combustion from its cold flow value due to turbulence from combustion. Figure 46 presents an extreme of these conditions where discharge coefficient is assumed to be unity and it was not possible to separate the two effects.

Pressure Profile. Pressure profile of the high pressure igniter is presented in Table 17 for a range of inlet conditions. Most of the tests were conducted using orifices located downstream of the igniter valves to increase the inlet pressure to approximately 375 psia (259 N/cm^2).

Combustor Temperature. The combustor flow was stratified with cool, fuel-rich gas cooling the throat convergent section and throat, while the core was oxidizer-rich. Test durations were approximately 1 second. At the conclusion of the test series, the igniter did not show any evidence of heating of the combustor or spark plug tips.

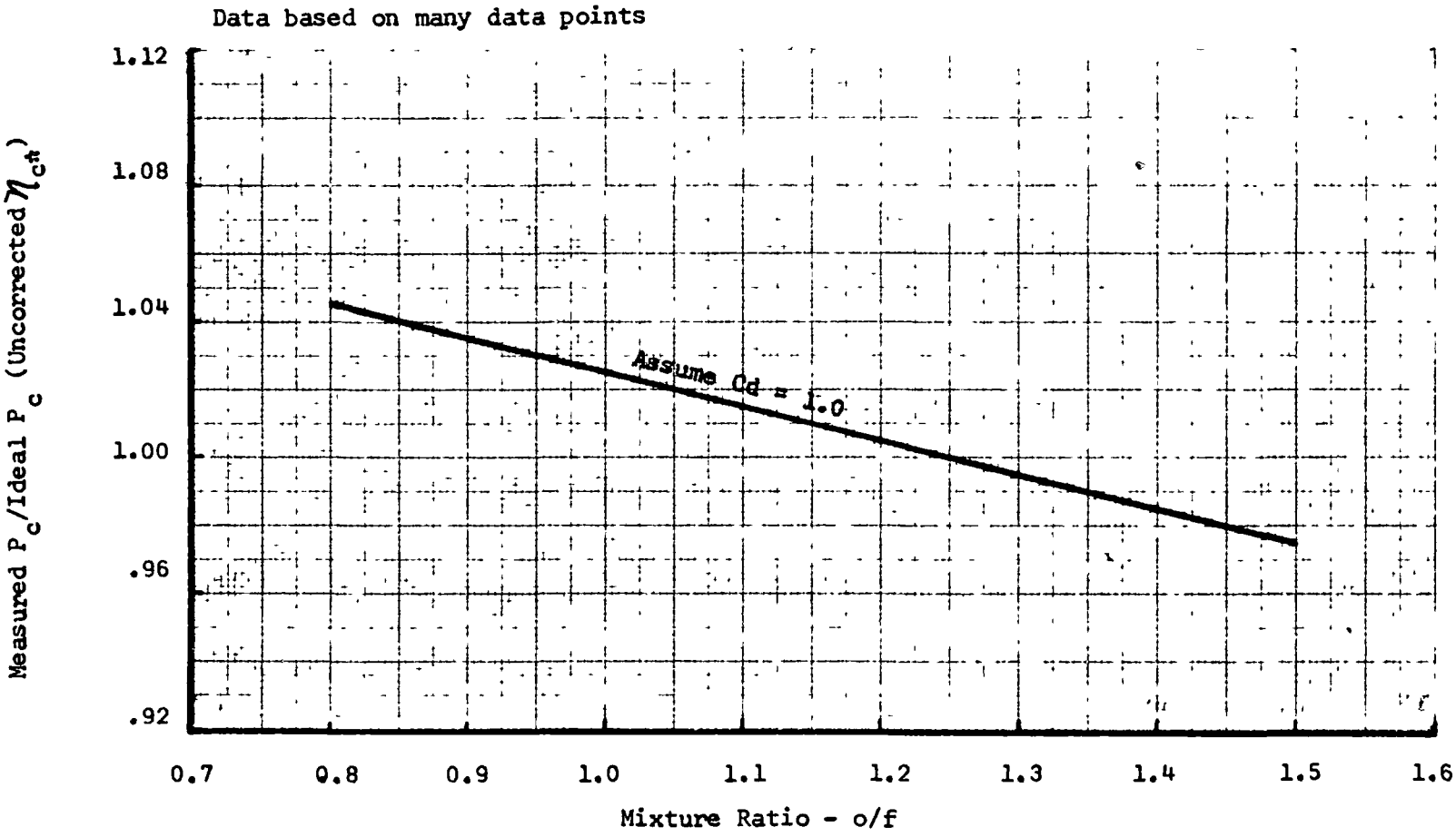


Figure 46. Ignited Combustion Performance and Discharge Coefficient

HIGH PRESSURE SPARK IGNITER PRESSURE PROFILE
TABLE 17

			Fuel		Oxidizer	
$\dot{W}$ lb_m/sec (Kg/sec)	MR o/f	P_c psia (N/cm^2)	Inj. psia (N/cm^2)	Inlet psia (N/cm^2)	Inj. psia (N/cm^2)	Inlet psia (N/cm^2)
.040 (.018)	0.8	226 (156)	309 (213)	375 (259)	288 (199)	367 (253)
"	1.0	230 (159)	297 (205)	353 (243)	309 (213)	402 (277)
"	1.5	240 (165)	281 (194)	319 (220)	345 (238)	465 (321)

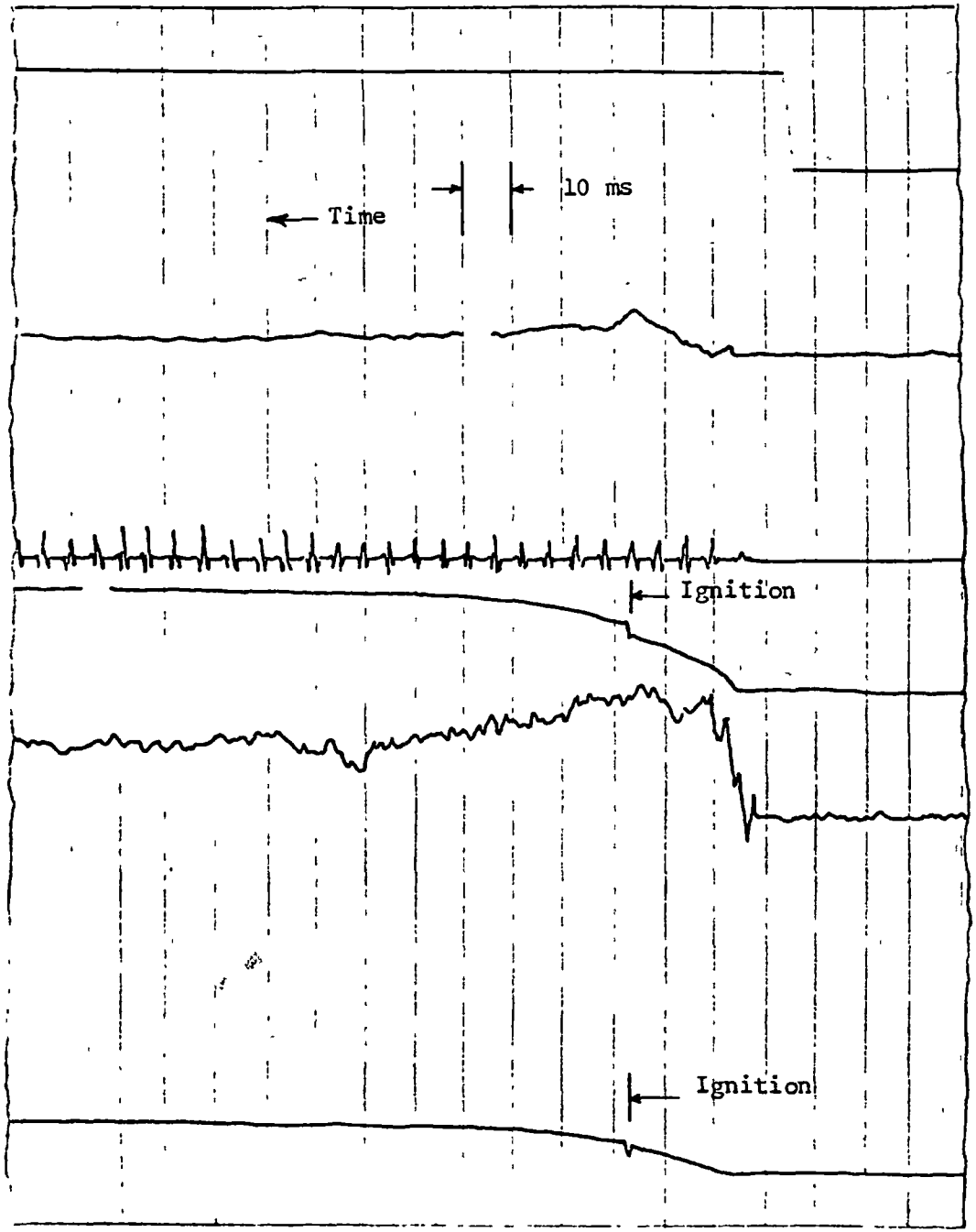
520 R (289 K) Propellant Temperature
Nozzles located in Fuel and Oxidizer Feed Line

Two temperature measurements (open tip thermocouples) were made: (1) combustion temperature probe at the convergent section and (2) spark plug tip measurement made with a "dummy" spark plug at the alternate location. These results indicate that after one second the combustor was near temperature equilibrium, and the igniter is capable of extended duration operation, being cooled only by its unique internal flow characteristics.

The combustion temperature probe (convergent section) was sensitive to immersion depth. At a distance of 0.25 inch (0.6 cm), as measured from the wall surface, the temperature would typically increase by less than 100° F (56 C) for a mixture ratio of 1.0:1 (o/f). At higher mixture ratios of 1.5:1 (o/f) the temperature would stabilize at up to 2200° F (1204 C). This indicates the presence of a cool fuel boundary layer that was at least 0.25 inch (0.6 cm) thick, and the boundary layer decreases as mixture ratio increases. When the thermocouple immersion depth was increased to 0.5 inch (1.3 cm), the probe would burn out at ignition and burn back to a depth of 0.3 inch (0.8 cm) at a mixture ratio of 1.0:1 (o/f). This further verified the presence of a fuel boundary layer to approximately 0.25 inch (0.6 cm) and a high temperature core.

Igniter Response. Typical igniter response is shown by the oscillograph trace in Fig. 47. Ignition occurred on the fifth spark 16 milliseconds (ignition delay) after inception of oxidizer flow, 25 milliseconds after start of fuel flow, and 33 milliseconds after electrical start. Pressure response measured to 90 percent of ignited chamber pressure was 55 milliseconds after electrical start. Propellant inlet conditions such as inlet pressure, propellant temperature, flowrate and mixture ratio did not have a significant effect on ignition delay or pressure response.

HIGH PRESSURE SPARK IGNITER RESPONSE



TEST NO. 82

P_c = 236 psia (163 N/cm^2)

$\dot{W}_T$ = 0.0399 lb$_m$/sec (0.018 Kg/sec)

MR = 1.02 o/f

Figure 47

A fuel lead of 10 milliseconds was used to avoid auto-ignition (as previously discussed). Thus, the local spark plug mixture ratio had to go through a fuel-rich transient. Thus, without a fuel lead the response would be less than 25 milliseconds from electrical start to ignition.

Inlet Conditions. The effect of propellant inlet conditions on ignition was investigated for variations in mixture ratio, flowrate, chamber pressure, and propellant temperature.

Mixture Ratio. Mixture ratio was varied from 0.8:1 to 1.4:1 (o/f) while stored energy was varied down to 12 millijoules. These tests are summarized in Table 18, and ignitions are shown in terms of number of no-ignitions, delayed ignitions (greater than 30 milliseconds), and ignitions. All mixture ratios at the center spark plug location resulted in ignition for a delivered spark energy of 19 millijoules, and ignitions were obtained at 1 millijoule.

Flowrate and Chamber Pressure. The flowrate was varied from the nominal (0.5 to 1 X Nominal) with a proportional change in chamber pressure. The throat area was increased (2 X Nominal), and the flowrate was again varied (1 to 1.5 X Nominal). These results are presented in Table 19. There was no significant trend in ignitions or energy for variations in flowrate at constant chamber pressure. There was a trend of energy vs chamber pressure. Lower chamber pressures required lower spark energy for rapid ignition whether the lower chamber pressure was obtained by decreased flowrate or increased throat area.

The nominal chamber pressure was changed from 230 to 120 psia (159 to 83 N/cm^2). This decision was based upon the fact that lower chamber pressure required

HIGH PRESSURE SPARK IGNITER

EFFECT OF MIXTURE RATIO VARIATION

TABLE 18

Test Phase	Spark Plug	Loc.	MR*	Nominal P_c psia	P_c N/cm^2	Flowrate* lb_m/sec	Flowrate* Kg/sec	Energy (mj) Stored	Energy (mj) Del.**	Ign.	Ign. Delay (ms)	No. of Tests
Ign.	J-2	Ctr.	1.40	230	159	.0400	.0182	68-210	12-43	Yes	<30	7
Eval.	"	"	1.01	"	"	.0401	.0182	68	12	No	-	1
"	"	"	"	"	"	"	"	44-68	6-12	Yes	>30	2
"	"	"	"	"	"	"	"	68-210	12-43	Yes	<30	8
"	"	"	0.82	"	"	.0389	.0177	68-97	12-19	Yes	<30	4
Spark	Dual	Ctr.	1.39	"	"	.0406	.0184	12	0.7	No	-	1
Energy	Gap	"	"	"	"	"	"	19	2	Yes	>30	1
"	"	"	"	"	"	"	"	12-35	0.7-4	Yes	<30	3
"	"	"	1.01	"	"	.0400	.0182	44	6	No	-	1
"	"	"	"	"	"	"	"	35-44	4-6	Yes	>30	5
"	"	"	"	"	"	"	"	44-97	6-19	Yes	<30	9
"	"	"	0.81	"	"	.0386	.0175	12-19	0.7-2	Yes	>30	2
"	"	"	"	"	"	"	"	12-68	0.7-12	Yes	<30	6
"	"	Side	1.42	"	"	.0404	.0183	68	12	Yes	>30	2
"	"	"	"	"	"	"	"	97	19	Yes	<30	1
"	"	"	0.99	"	"	.0404	.0183	35	4	No	-	1
"	"	"	"	"	"	"	"	68	12	Yes	>30	2
"	"	"	"	"	"	"	"	68	12	Yes	<30	1
"	"	"	0.81	"	"	.0406	.0184	35	4	No	-	1
"	"	"	"	"	"	"	"	68	12	Yes	>30	1
"	"	"	"	"	"	"	"	97	19	Yes	<30	1

* Average values of flowrate and mixture ratio. Ambient temperature propellants.
** Energy dissipated during storage cycle not accounted for.

TABLE 19

HIGH PRESSURE SPARK IGNITER
EFFECT OF FLOWRATE AND CHAMBER PRESSURE VARIATION

Test Phase	Spark Plug	Loc.	MR*	Nominal P_c psia	P_c N/cm^2	Flowrate* $\dot{m}$ lb/sec	Flowrate* Kg/sec	Energy (mj) Stored	Energy (mj) Del.**	Ign.	Ign. Delay (ms)	No. of Tests
Spark	Dual	Ctr.	1.01	230	159	.0400	.0182	44	6	No	-	1
Energy	Gap	"	"	"	"	"	"	35-44	4-6	Yes	>30	5
"	"	"	"	"	"	"	"	44-97	6-19	Yes	<30	9
Oper.	"	"	1.03	175	121	.0307	.0139	26	3	No	-	1
Limits	"	"	"	"	"	"	"	26	3	Yes	>30	2
"	"	"	"	"	"	"	"	44-68	7-14	Yes	<30	2
"	"	"	0.98	115	79	.0207	.0094	19	2	No	>30	1
"	"	"	"	"	"	"	"	26-44	4-8	Yes	<30	2
"	"	"	1.09	110	76	.0403	.0183	2	0.1	Yes	>30	2
"	"	"	"	"	"	"	"	12-44	0.9-8	Yes	<30	5
"	"	"	1.08	165	114	.0602	.0273	12	0.8	No	-	1
"	"	"	"	"	"	"	"	19-68	2-14	Yes	>30	4
"	"	"	"	"	"	"	"	19-44	2-7	Yes	<30	6
"	"	Side	1.12	110	76	.0402	.0183	12-26	0.9-4	Yes	>30	4
"	"	"	"	"	"	"	"	26-68	4-16	Yes	<30	2

* Average values of flowrate and mixture ratio. Ambient temperature propellants.
** Energy dissipated during storage cycle not accounted for.

lower energy and voltage. Reduction in both energy and voltage aided in the miniaturization of the integrated spark/exciter and reduction in power requirements for this unit. Both factors will reduce RFI.

Propellant Temperature. Propellant temperature was varied over the nominal range of 200 to 800 R (111 to 444 K) at a mixture ratio of 1.0:1 (o/f). These results are summarized in Table 20. There was no apparent change in the required energy at propellant temperatures above ambient. At below ambient propellant temperatures, the results are inconclusive.

On below ambient temperature tests, satisfactory ignitions were obtained with low energy levels (4 mj). However, ignitions were erratic due primarily to problems with the workhorse type electrical equipment. An oscilloscope and polaroid camera were employed to monitor the spark voltage and current. It became evident that the spark energy was being drained during the charge cycle of the exciter and that the energy delivered during the spark cycle was only a portion of the available energy. The actual delivered spark energy could not be ascertained from the polaroid records, and the values of delivered spark energy in Table 20 represent the maximum delivered if no energy was dissipated during the charge cycle. It is estimated that approximately up to 80% of the energy was being drained during the charge cycle and it is questionable if actual sparking at the plug tip was obtained. (The electrical system is discussed in more detail below.)

Spark Ignition System. The effect of spark ignition system on ignition was investigated for variations in spark energy and spark plug location. The spark plug selected from Task I testing was the 0.025-inch (0.064 cm) dual recess gap plug. A variable energy exciter fabricated during Task I was modified after the initial checkout test series and was used to provide the inductive spark energy.

Inductive Unit Operation. The workhorse inductance exciter unit was capable of varying stored energy and spark rate. During Task I laboratory testing, the usual mode of operation was a single spark. A predetermined stored

HIGH PRESSURE SPARK IGNITER
EFFECT OF TEMPERATURE VARIATION

TABLE 20

MR*	Nominal P_c psia	N/cm^2	Flowrate* lb_m/sec	Kg/sec	Fuel Temp.* R	K	Oxid. Temp* R	K	Energy (mj) Stored	Del.**	Ign.	Ign. Delay (ms)	No. of Tests
1.17	115	79	.0447	.0203	781	434	626	348	12-26	0.9-4	Yes	> 30	4
"	"	"	"	"	"	"	"	"	2-44	0.1-8	Yes	< 30	4
1.25	110	76	.0445	.0202	651	362	633	352	12	0.9	No	-	1
"	"	"	"	"	"	"	"	"	12-26	0.9-4	Yes	> 30	2
"	"	"	"	"	"	"	"	"	26-97	4-26	Yes	< 30	4
1.09	110	76	.0403	.0183	520	289	520	289	2	0.1	Yes	> 30	2
"	"	"	"	"	"	"	"	"	12-44	0.9-8	Yes	< 30	5
0.91	105	72	.0369	.0168	348	193	350	194	26-97	3-21	No	-	3
"	"	"	"	"	"	"	"	"	44-170	7-38	Yes	< 30	5
0.97	100	69	.0355	.0161	225	125	357	198	26-35	2-3	No	-	4
"	"	"	"	"	"	"	"	"	68-170	8-28	Yes	> 30	4
"	"	"	"	"	"	"	"	"	44-68	4-8	Yes	< 30	3

* Average values of mixture ratio, propellant temperature, and flowrate. Dual gap plug at center location.

** Energy dissipated during storage cycle not accounted for.

energy could be obtained by a calibrated dial setting. The energy delivered by the unit was effected by both spark plug media and inherent inadequacies of the unit's high voltage transformer. This latter problem precluded proper evaluation of the former dependent variable. The transformer had been manufactured out of specification and would quickly saturate during the multiple spark mode as well as become intolerably inefficient (< 5 percent) at voltage settings above 10 KV. This was not a significant factor during the low pressure igniter test effort since ignition usually occurred on the second to fourth spark, and the 10 KV potential and low energies were more than sufficient for sparking at the low pressures. When this unit was used for high pressure operation, the delivered energy pulse was insufficient to cause consistent sparking. While the inductive exciter unit was being modified, the J-2 variable capacitance unit was used to obtain initial igniter combustion characteristics. This unit was capable of variable voltage to 25 KV and variable energy to 3 joules. The delivered energy efficiency of the unit is unknown (and is also influenced by the spark plug media) and was not assessed due to the temporary nature of the test use. The test results did indicate that at least 20 KV settings were required for repeated ignitions.

Modified Inductive Unit Operation. The modified workhorse inductive unit was used for the planned test series. This calibrated unit was capable of storing a predetermined spark energy. A laboratory calibration of delivered vs stored energy was made in air at ambient pressure, with the dual recessed gap plug.

During the cold propellant temperature test series, the delivered spark voltage and current (energy) was monitored by means of an oscilloscope and polaroid camera. These results revealed that during the storage cycle there was output voltage and current (energy flow), and much of the stored energy was being

dissipated in the secondary circuit. Subsequent evaluation showed that energy was also being dissipated occasionally during the charge cycle with ambient temperature propellants. In many instances the character of the secondary current and voltage indicated no spark discharge.

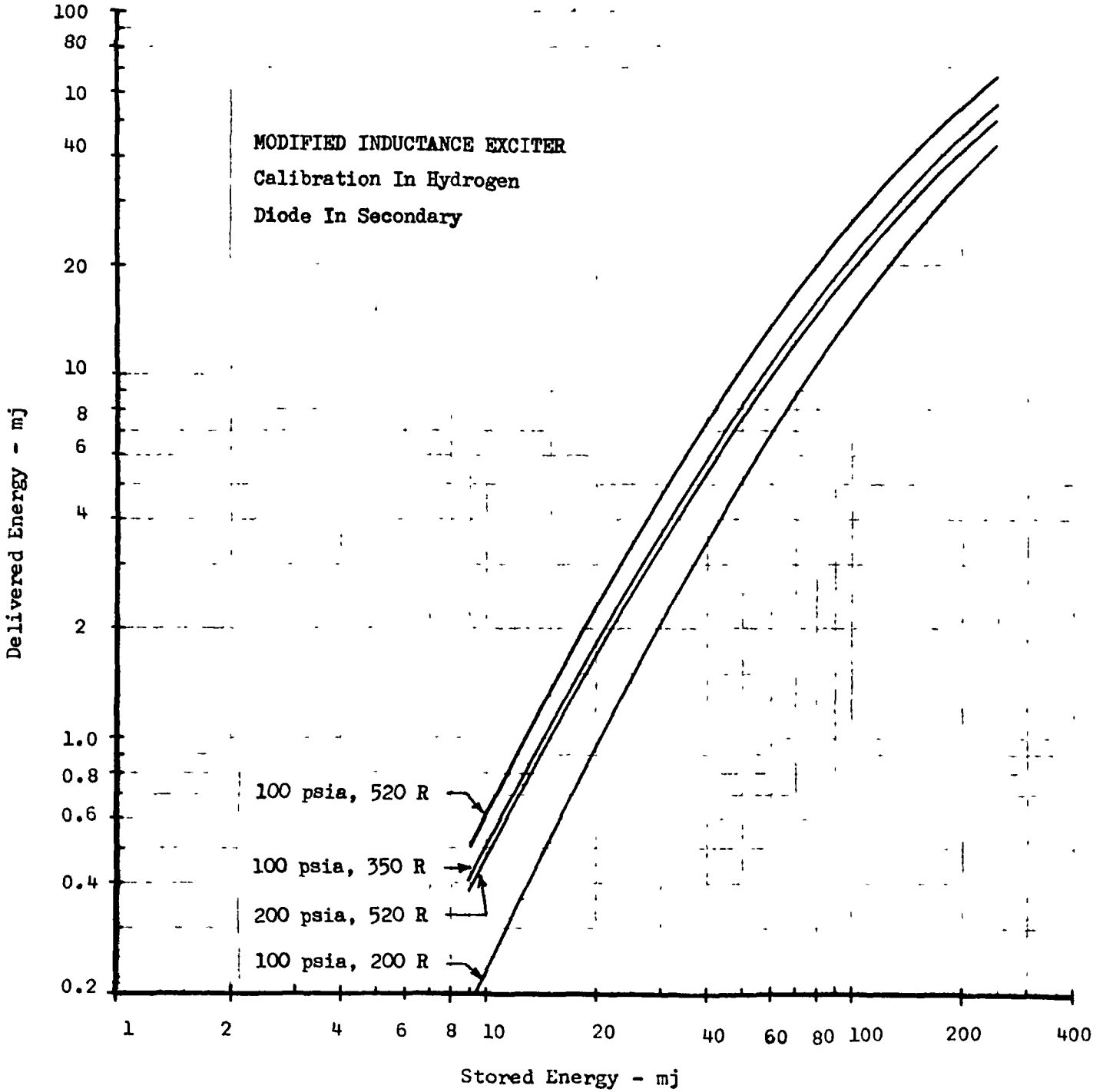
The unit was further modified by installing a diode in the secondary circuit to prevent current flow during the charge cycle. The unit was then calibrated in hydrogen and nitrogen to further define the delivered spark energies in this test series. These results are shown in Fig. 48. With no diode in the circuit, there is energy dissipation prior to the spark. Therefore, the results of Fig. 48 represent a conservative estimate of the delivered energies during the high pressure spark effort.

Spark Energy. Ignition was achieved at all conditions with a delivered spark energy of 19 millijoules maximum. With the center spark location, 12 millijoules delivered was sufficient for repeated ignitions within 15 milliseconds after oxidizer flow. At the lower chamber pressure of 120 psia (84 N/cm^2), ignition was achieved with as low as 1 millijoule delivered. Considering the energy dissipation problem previously discussed, the actual spark energy required was less than 12 millijoules, and it appears that the design goal of the integrated spark/exciter of 30 millijoules will have an ample margin to assure ignition.

Spark Plug Type. Two spark plugs were used on the high pressure igniter. A J-2 plug was used for initial igniter evaluation and the 0.025-inch (0.064 cm) dual recess gap spark plug selected from Task I evaluation was used for subsequent spark evaluation and operational limits tests. Both spark plugs performed equally well.

Figure 48

Delivered versus Stored Spark Energy-High Pressure Spark Igniter



Spark Rate. The spark rate was varied from 200, 150 to 100 cps with nominal test conditions and sequence. There was no influence of spark rate on ignition and ignition was achieved on the spark which occurred between 10 and 20 milliseconds after start of oxidizer flow.

Spark Plug Location. The igniter had the option of two plug locations which were the top of the oxidizer dome and the side of the oxidizer dome. Ignition occurred at both locations down to the same energy levels. Ignitions at the center location were rapid (less than 15 milliseconds ignition delay) even at low energy levels. The side location had greater ignition delays at the lower energy levels (> 30 milliseconds).

CONCLUSIONS FROM THE SPARK "IGNITER ONLY" TEST PROGRAM

Both the high pressure and low pressure spark igniter configurations demonstrated reliable ignition and sustained burning at their respective design conditions (inlet temperature and pressure) and over the specified range of propellant inlet temperatures. Ignition was demonstrated to be insensitive to wide variations in inlet conditions such as pressure, mixture ratio, and sequencing.

The internal flow of both igniter configurations was shown to be highly stratified with a relatively thick fuel boundary layer on the wall and a hot, oxidizer-rich core. This unique flow allows the igniters to be operated for extended durations without any adverse heating of the igniter or spark plugs.

The response of both ignition systems was demonstrated to be less than 50 milliseconds from electrical start to 90 percent of chamber pressure.

The design goal of 30 millijoules stored for the integrated spark/exciter will have sufficient margin to assure ignition of both ignition systems. The

minimum required delivery energy for reliable ignition was found to be 3 millijoules for the low pressure configuration and 12 millijoules for the high pressure configuration.

AUTO-IGNITER TESTING

The purpose of Task II of the SS/APS Ignition System Program is to hot fire the igniter designed and fabricated during Task I. Task II is divided into two phases: (1) "igniter only" tests and (2) igniter/thruster tests. During this report period, the test plan for the "igniter only" test phase for the resonance igniter was prepared, submitted and approved. The igniter/thruster test plan will be submitted separately. All "igniter only" tests will be performed at the Los Angeles Division.

Objectives

The principal objectives of the Task II "igniter only" test phase are to determine the operating limits and characteristics of the optimized resonance igniter which resulted from the Task I phenomena tests. The test plan reflects the approach to be followed in order to achieve these objectives and also includes tests designed to check the effectiveness of different resonance tube materials, and the elimination of system problems (which were encountered during Task I) such as propellant supply pressure overshoots.

The igniter tests will be performed using gaseous hydrogen and gaseous oxygen propellants and with the igniter exposed to vacuum conditions prior to each start. The igniters will be instrumented to measure transient and steady-state values of critical temperatures and pressures. Ignition delay time, and pressure and temperature response of the effluent gas from the igniter will be

determined. Operating limits, including propellant pressures and temperatures, will be established.

The optimized resonance igniter configuration (Fig. 32), which resulted from the Task I tests, will be evaluated under hot-fire conditions. The Task II test results will provide design criteria and operating limits for the Task III ignition system design.

Facility Description and Operation

The igniter test effort will be conducted at the Los Angeles Division Thermodynamics Laboratory. A schematic of the propellant system is shown in Fig.49. This facility was used during the Task I resonance phenomena tests and Task II spark igniter tests.

Propellant Systems. Feed systems for both propellants are similar in size and configuration. The propellant is stored in high pressure bottles and is supplied through a 1-1/2-inch (3.8 cm) system and pressure regulator to the test cell. A calibrated sonic venturi is incorporated by a bypass line and valve. This feature is a convenient method of calibrating the facility, igniter hardware and subsonic flowmeters. During blowdowns, the bypass valve is closed and flow is measured and controlled by the sonic venturi while system/hardware parameters are measured. During ignition tests, the bypass valve is opened and the effect of the sonic venturi is negated.

An aluminum heat sink exchanger is used to provide conditioned propellant to a given temperature from 200 to 800 R (111 to 444 K). The heat exchanger has a propellant coil, liquid nitrogen coil and electric heating coil embedded within an aluminum casting. Cold temperature conditioning is achieved by flowing

HIGH PRESSURE AUTO-IGNITER TEST FACILITY SCHEMATIC

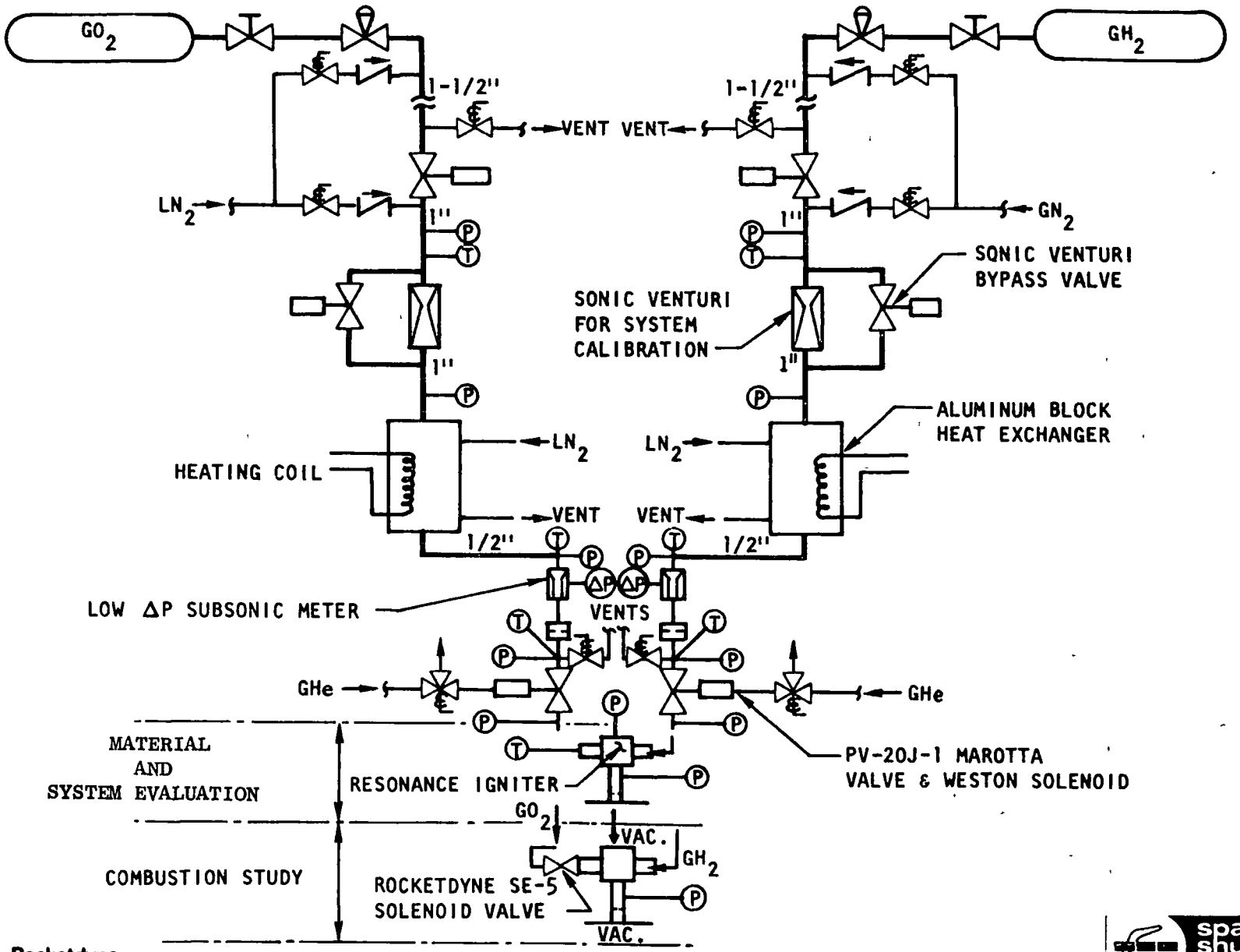


Figure 49

Rocketdyne
North American Rockwell
6633 Canoga Ave Canoga Park Calif 91304

space shuttle engine
AUXILIARY PROPULSION SYSTEM

liquid nitrogen and using the heating coil in an on/off mode to achieve fine control of the aluminum block temperature. Hot temperature conditioning is achieved by using the heating coil only. During ambient temperature tests, the heat exchanger is bypassed to eliminate the heat exchanger pressure drop.

Downstream of the heat exchanger on the high pressure system (Fig. 49), the system is close-coupled to reduce system mass and time required to temperature condition the system. Close-coupled to the igniter valves is a low pressure drop subsonic venturi to measure transient and steady-state flowrate and a bleed point to precondition the system temperature up to the valve inlet.

System Control. All tests are conducted using an automatic sequencer. The sequence includes operation of the fuel valve, oxidizer valve and bleed valves.

The sequencer is capable of controlling the valves to any specified relative position in time within 1 millisecond. Prior to each test series, the sequence is verified with the systems pressurized with GN_2.

A continuous flow of propellants at approximately the test flowrates is maintained through a vent immediately upstream of the igniter valve. In this manner, the specified propellant temperature and pressure is maintained at the valve inlet. During the test, the vent valves are sequenced closed immediately before the igniter valves are sequenced open.

Test Matrix

The test matrix for the resonance igniter is presented in Table 21. Four phases of testing are indicated: (1) resonance tube material evaluation, (2) determination of operational limits, (3) system evaluation, and (4) oxygen augmentation. A test schedule is shown in Fig. 50.

TABLE 21

AUTO-IGNITER TEST PROGRAM

TEST	VARIABLES	RESULTS
1-15	Thermocouple at end of resonance tube - no heat exchanger in line - different resonance tube materials - uncooled L* spacer	Effect of resonance tube materials on resonance temperature - effect of mixing chamber volume
16-25	Oxygen valve delay - constant M.R.	Ignition delay - combustion temperature
26-40	O_2 flowrate (constant H_2 flowrate)	Mixture ratio limit - ignition delay - combustion temperature - spacer skin temperature
41-55	Heat-exchanger in line	Elimination of supply pressure overshoots
56-65	Thermocouple at end of resonance tube - heat-exchanger in line (ambient H_2)	Effect of heat-exchanger on resonance temperature
66-80	Thermocouple at end of resonance tube - H_2 temperature	Resonance temperature as a function of H_2 temperature
81-105	O_2 flowrate (constant H_2 flowrate) - O_2 & H_2 temperatures (down to 220°R)	Mixture ratio limits (for different propellant temperatures) ignition delays - combustion temperatures
106-130	O_2 & H_2 pressures O_2 & H_2 at ambient temperatures	Mixture ratio limits (for different propellant pressures) ignition delay - combustion temperatures
131-145	O_2 cooling liner - O_2 cooling flowrate - (ambient H_2)	Combustion temperatures with O_2 augmentation

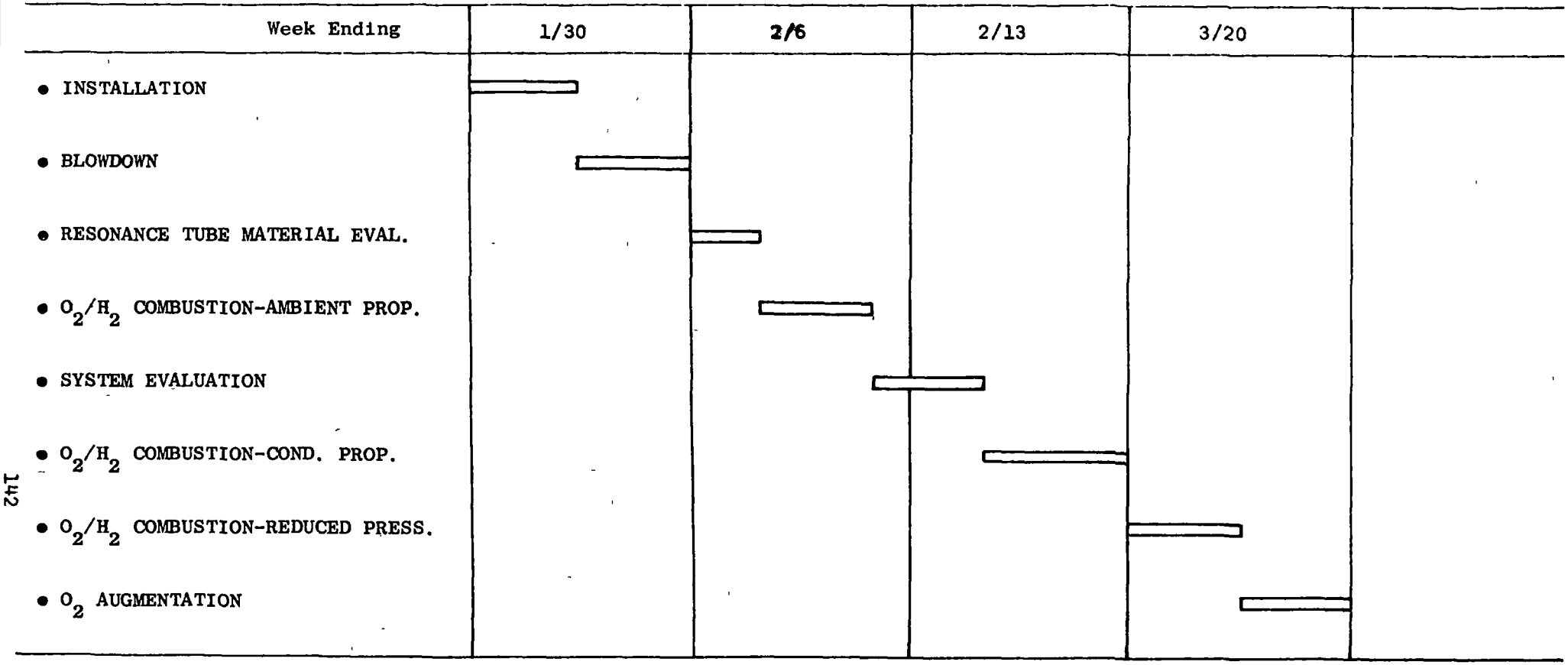


Fig. 50. Auto-Igniter Test Activity Schedule

Resonance Tube Material Evaluation (Tests 1-15 and Tests 66-80). Part of the Task I effort consisted of testing the performance of two resonance tubes of identical geometries (configuration I) but made out of two different materials. One of these tubes was made out of quartz, the other was made out of stainless steel. When using hydrogen only and measuring the resonance temperature as a function of time, the quartz tube resulted in higher responses (1000 R temperature rise in 22 milliseconds) than obtained with the stainless steel tube. The reason for these results was that quartz, because of its low thermal conductivity, had low heat-transfer losses. Although both the quartz and stainless steel tubes produced repeated and reliable ignitions of oxygen/hydrogen when these propellants had ambient inlet temperatures, the quartz resonance tube was chosen for the ensuing combustion experiments with low temperature (down to 285 R) propellants. During the latter tests, it was observed that the range of mixture ratios, which resulted in reliable ignitions, was reduced. In order to extend the operational range of the igniter for low temperature propellants, tests will be performed during Task II with a resonance tube made out of aluminum silicate material which has a low thermal conductivity and potentially higher thermal shock resistance than that of quartz. These tests will be performed with hydrogen at ambient temperatures (tests 1-15) and reduced temperatures down to 220 R (tests 66-80) and measurements will be made of the resonance temperature-time characteristics using a thermocouple located at the end of the resonance tube. The thermocouple will be held in place by means of a thermocouple holder.

The results of the tests will be compared to those obtained during Task I (a check of the quartz resonance tube performance will be made with the Task II igniter) and a decision will be made as to which resonance tube material will

be used in the combustion experiments to be discussed in a later paragraph. It should be noted that most of the tests discussed above will be performed with the uncooled L* spacer and throat adapter to simulate the exact geometry of the Task I optimized igniter configuration. Several tests will be run without the L* spacer to determine the effect of mixing chamber volume and/or hydrogen jet pressure ratio transient (P_T/P_{MC}) on the resonance temperature-time characteristics.

Operation Limits (Test 16-40 and Tests 81-130). During this test series, hydrogen and oxygen will be used to determine the range of satisfactory operation of the resonance igniter.

Using ambient temperature propellants, tests 16 through 40 will consist of a systematic variation of mixture ratio, i.e., varying the oxygen flowrate while keeping the hydrogen flowrate at its nominal value (0.02 lb/sec). For each mixture ratio the minimum hydrogen valve opening time lead (time lead with respect to oxygen valve opening) will be determined. The uncooled L* spacer to be used in these tests will be instrumented with 3 thermocouples to measure the circumferential skin temperature distribution.

Tests 81 through 105* will be made with propellant temperatures varying between 200 and 800 R (111 to 444 R). At each particular temperature condition, the range of mixture ratios and valve timings which will result in repeated and reliable ignitions will be determined. Throughout this test series, the hydrogen pressure will be maintained at or near the nominal pressure of 375 psia (2.585×10^6 N/m^2).

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* Note that tests 41 through 65 (which relate to system evaluation tests) will be discussed in a paragraph below.

Tests 106 through 130 will be made at reduced pressures (down to approximately 50 psia hydrogen inlet pressure). At each pressure level, the operational mixture ratios and valve timings will be determined. These tests will be made with ambient temperature propellants.

System Evaluation (Tests 41-65). During the Task I tests, it was observed that the introduction of the hydrogen heat-exchanger into the system caused supply pressure overshoots (time dependent excess pressures) which resulted in anomalous reductions in the resonance temperature response. In order to eliminate these pressure overshoots, a series of tests will be made wherein an accumulator will be placed between the heat-exchanger exit and the inlet to the hydrogen valve (Marotta). The resonance temperature-time characteristics will be investigated, first with ambient temperature hydrogen and then with inlet hydrogen temperatures varying between 200 and 800 R (111 and 444 K).

Oxygen Augmentation (Tests 131-145). Data obtained during the thruster tests (NASA Contract NAS 3-14352) with spark and catalytic igniters indicated that igniter (torch) temperatures greater than 2000 R (1110 K) were desirable for reliable ignition of SS/APS 1500-lb thrust engines. Also, if the igniter is to be used ultimately without separate valving (duration of igniter firing equal to thruster duration), or if the igniter is to be used with separate valves for minimum impulse attitude control, some form of igniter cooling will be required.

In order to cool the igniter hardware and increase the temperature of the igniter combustion products, gaseous oxygen will be used as a coolant (in the down-pass dump mode) which will be injected downstream of the igniter exit to provide oxidizer augmentation.

The resonance igniter proper will be run at low mixture ratios (approximately 0.8), and the secondary oxygen flowrate will be maintained at 0.054 lb/sec (0.24 Kg/sec) to achieve an overall total mixture ratio of 3.5 downstream of the igniter exit. To introduce the secondary oxygen into the igniter hardware, a bypass line will be placed between the oxygen Marotta valve and the SE-5 valve. The bypass line will include an orifice to measure the secondary oxygen flowrate. A thermocouple (10 mil rhenium/platinum) will be placed downstream of the igniter to monitor the temperature increase due to oxygen augmentation.

Instrumentation

Instrumentation requirements are presented in Table 22. Sufficient pressure and temperature sensors are used to establish and monitor the system/hardware conditions. Data acquisition includes a high-speed digital system, a high-frequency oscillograph recorder and a 6-channel high response Brush recorder. Dial indicators will be located on the control console for system setup.

The digital system is an Astro Data System capable of 6600 samples per second with inputs from up to 100 sensors. Since the instrumentation list has less than 25 inputs, each parameter will be multiplexed four times to achieve a sample rate of 264 times per second per parameters. The Astro Data System records data with an IBM 360 compatible binary format on magnetic tape for subsequent computer data reduction.

A high-frequency Kistler water-cooled transducer will be recorded with other selected system parameters on a high-frequency oscillograph recorder to establish the transient conditions and ignition delay. This recorder outputs a permanent strip chart at speeds up to 128 inches per second.

TABLE 22

IGNITER INSTRUMENTATION LIST

System	Parameter	Range	Recorder Precision, percent			
			Digital	Osc.	Brush	Indication
Fuel	Calibration Venturi u/s Pr	0-1000 psig	1/2	-	-	2
	Calibration Venturi u/s T	0/150° F	1	-	-	-
	Conditioner u/s Pr	0-1000 psig	1/2	-	-	-
	Flow Meter u/s Pr	0-500 psig	1/2	10	-	-
	Flow Meter u/s T	200/800 R	1	-	-	-
	Flow Meter Δ P	0-20 psid	1/2	10	1	-
	Valve u/s Pr	0-500 psig	1/2	-	1	2
	Valve Bleed T	200/800 R	-	-	-	2
	Injection Pr	0-500 psig	1/2	10	1	-
Oxidizer	Calibration Venturi u/s Pr	0-1000 psig	1/2	-	-	2
	Calibration Venturi u/s T	0/150 F	1	-	-	-
	Conditioner u/s Pr	0-1000 psig	1/2	-	-	-
	Flow Meter u/s Pr	0-500 psig	1/2	10	-	-
	Flow Meter u/s T	200/800 R	1	-	-	-
	Flow Meter Δ P	0-20 psid	1/2	10	1	-
	Valve u/s Pr	0-500 psig	1/2	-	1	2
	Valve Bleed T	200/800 R	-	-	-	2
	Injection Pr	0-500 psia	1/2	10	-	-
	Coolant Flow Meter Δ P	0-20 psid	1/2	-	1	-
Igniter	Base Pc	0-500 psia	1/2	10	1	-
	High Frequency Pc	0-1000 psig	-	10	-	-
	Vacuum P	10^{-4} mm Hg	-	-	-	2
	Space Skin T	0-3000R	-	-	1	2
	Resonance T	0-3000R	1/2	10	1	-
Events	Fuel Valve Signal	-	X	X	X	-
	Oxidizer Valve Signal	-	X	-	X	-
	SE-5 Valve	-	X	X	X	-
	Fuel Bleed Valve Signal	-	-	-	X	-
	Oxid Bleed Valve Signal	-	-	-	X	-
	Time Reference	1 cps	X	X	X	-

A 6-channel Brush recorder will be used for on-the-spot monitoring of test results. This recorder is capable of moderately high response and accurage quantitative data. In addition, the recorder contains event channels for recording the electrical valve sequence.

Documentation of Results

A file of test records will be maintained, and this file will include the strip charts and computer data reduction outputs. This test series will be documented by an internal report and in appropriate monthly and quarterly reports.

Data Reduction

The Astro Data magnetic tape will be reduced by a computer data reduction program. This program has been written to reduce digital counts to pressures and temperatures in engineering units. The program will calculate flowrates and mixture ratio from the subsonic meters, using input tables of real gas properties for each propellant and the in-place calibration factors for each meter as determined by the system calibration blowdowns.

Status

As scheduled, the resonance igniter has been installed in the test facility and blowdown tests have been completed. A brief evaluation of resonance tube materials will start at the beginning of the next report period. In accordance with the above discussions, system and combustion tests will be performed immediately after the material evaluation tests. (This test program was successfully completed one week ahead of schedule, 13 February 1971.)

THRUSTER IGNITION TESTING

The low pressure spark igniter and thruster are to be tested to assure that the igniter energy is sufficient to provide rapid ignition of the main

propellants. The test plan was submitted January 1971 and the assembly was installed on the facility. (Subsequent to the end of the quarterly report period but during the writing of this report, the low pressure thruster igniter program was successfully completed. Successful ignitions were obtained with spark igniter flowrates of 0.25 to 1.0 percent of thruster flowrates and igniter mixture ratios of 0.8:1 to 1.5:1 (o/f). The thruster response from electrical signal to 90 percent chamber pressure was also demonstrated by signaling the thruster and igniter valves simultaneously.)

Objective

This test series will be performed with a low pressure spark igniter assembly, uncooled workhorse thrust chamber, and concentric orifice injector to determine the effects of igniter energy on thruster ignition delay. These tests will provide thruster transient (ignition delay) data as a function of igniter flowrate and mixture ratio (energy).

The low pressure augmented spark igniter (ASI) will be used with ambient propellants. The uncooled workhorse thrust chamber and the concentric orifice injector from Contract NAS 3-14352 will be used for all tests with ambient propellants at a chamber pressure of 15 psia (10.35 N/cm^2) and a mixture ratio of 2.9:1 (o/f).

Igniter flowrate and mixture ratio will be systematically varied to determine the effects of igniter energy on thruster ignition delay. All thruster parameters will be held constant at nominal conditions.

Test Matrix

The test matrix for the low pressure igniter/thruster test effort is presented in Table 23. This effort consists of igniter energy evaluation and igniter/thruster response demonstration. Testing will be conducted in conjunction

TABLE 23

LOW PRESSURE THRUSTER/IGNITER TEST MATRIX

Test No.	Thruster			Igniter			Results
	P_c psia	P_c N/cm^2	M o/f	$\dot{W}$ lb_m/sec	$\dot{W}_T$ Kg/sec	MR o/f	
1	15	10.35	2.5	0.04	.018	1.5	Ignition Delay vs Igniter W
2	15	10.35	2.5	0.04	.018	1.0	Ignition Delay vs Igniter MR
3	15	10.35	2.5	0.04	.018	0.8	
4	15	10.35	2.5	0.02	.009	1.5	
5	15	10.35	2.5	0.02	.009	1.0	
6	15	10.35	2.5	0.02	.009	0.8	
7	15	10.35	2.5	TBD	TBD	TBD	Demonstrate Response of Igniter/Thruster

with the Hydrogen-Oxygen APS Engine Contract (NAS 3-14352) test effort in order to take full advantage of hardware configurations and facility operations which are applicable to the igniter test effort. Tests shown on the test matrix will be accomplished during early February 1971.

Igniter Energy Evaluation. This test series will evaluate the capability of the igniter to provide rapid ignition of the main propellant flowrate for a range of igniter energy. Igniter energy will be varied by changing igniter mixture ratio from 0.8:1 to 1.5:1 (o/f). Thruster transients and ignition delay will be determined as a function of igniter flowrate and mixture ratio.

Igniter/Thruster Response Demonstration. The capability of the igniter/thruster to be ignited within the specified time limitation (50 milliseconds) will be demonstrated. The simplest sequence and feed system, which is feasible when this test phase is conducted, will be used.

Test Hardware

Igniter. Based on the results of Task I, spark igniters have been designed and fabricated for the high pressure and low pressure SS/APS application. The low pressure igniter has been successfully check-fired at the LAD igniter facility. These tests demonstrated reliable ignition of the igniter with a spark frequency of 200 cps and spark energy of 3 millijoules. These data have been used in the design of the fixed energy integrated spark plug/exciter unit which will be fabricated and tested later in this program.

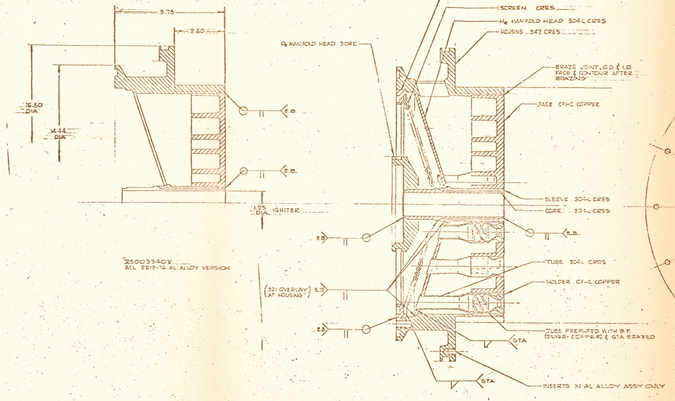
Thruster Assembly. The thruster assembly consists of an uncooled workhorse thrust chamber and concentric orifice injector. These components have been previously successfully hot fired on Contract NAS 3-14352. This fully checked-out

thruster assembly and facility should minimize operational problems for this program.

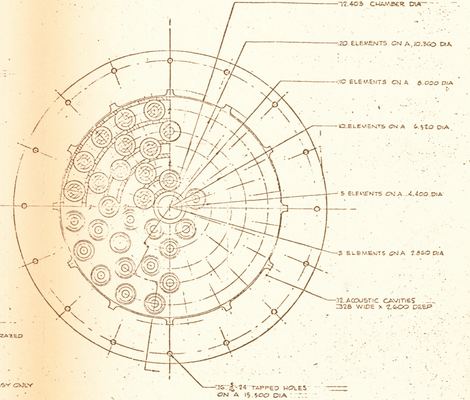
Injector. Two low pressure, concentric orifice injector designs have been detailed per task XII of NAS 3-14352 (Hydrogen-Oxygen APS Engines). Upon NASA-LeRC approval, these injectors were fabricated (Task XIII) and the concentric orifice injector has been hot fired (Task XIX) to establish performance, heat flux, and durability characteristics. Two injector designs have been generated--one for a dump-cooled thrust chamber with the injector designed for a core mixture ratio of 2.9:1 (o/f) and one for INTEREGEN-cooled thrust chamber with the injector designed for a core mixture ratio of 3.1:1 (o/f). The INTEREGEN coolant injector will be used for the ignition tests. Since the feasibility of a low pressure thruster in the space shuttle application will depend somewhat on development of a lightweight design, the injector was fabricated of aluminum.

The injector/manifold assemblies (RS003335X and RS003340X) are shown in Fig . The manifold is designed to be part of the test facility and the elements or core of the injectors are removable. This design approach reduces the number of manifolds to be fabricated and permits greater accessibility to the injector elements during fabrication of the injector cores.

The injector assembly is comprised of two basic assemblies: the fuel and oxodizer manifold and the injector core. The fuel and oxidizer manifold (RS002795X) shown in Fig. 52 is fabricated of stainless steel and is comprised of a tapered fuel manifold, an oxidizer inlet manifold, and a ring to which the injector cores are bolted and through which engine thrust is transmitted during engine operation.



FOLDOUT FRAME 1



FOLDOUT FRAME 2

FOLDOUT FRAME 3

FOLDOUT FRAME 4

LOX PRESSURE, CENTERING INJECTOR ASSY

J 02602 FIG. 51

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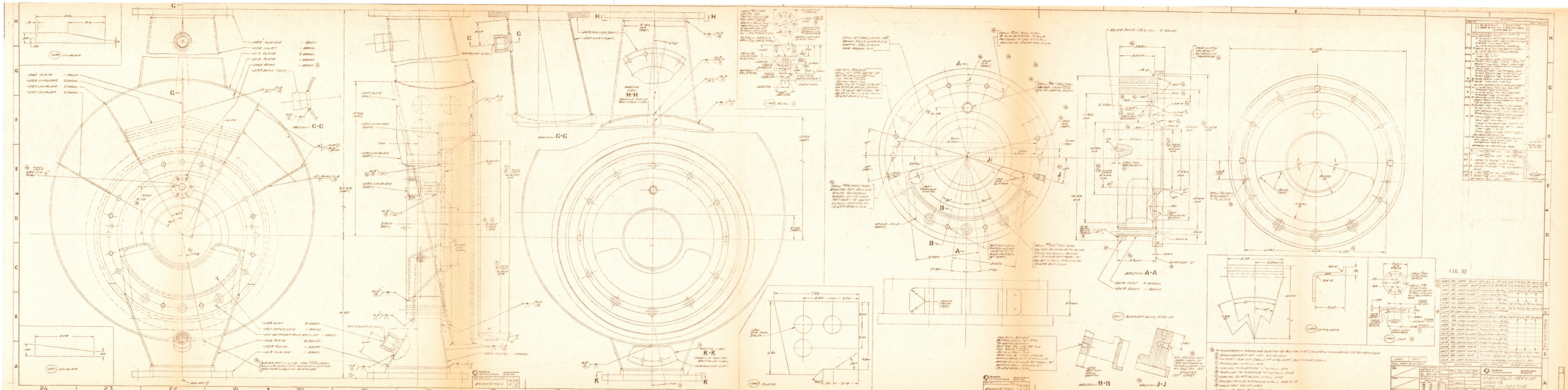

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

FOLDOUT FRAME 4

FOLDOUT FRAME 5

The oxidizer dome incorporates provision for mounting either a catalytic or spark igniter. A manifold is located just upstream of the exit cone interconnected to the oxidizer manifold. If oxygen augmentation flow is required for ignition purposes, orifices can be machined into the manifold through the exit cone to augment the ignition.

Heat Sink Thrust Chamber Assembly. The heat sink thrust chamber assembly (Fig. 53) includes a nozzle, various spacers for L* changes, and a film coolant manifold assembly. The basic configuration, consisting of the longer nozzle and the minimum L* spacer, duplicates the projected geometry of subsequent actively cooled flight-type thrust chambers with an injector-to-throat length of 8 inches (20.4 cm) and L* of 12 inches (30.5 cm).

The nozzles and spacers are fabricated from 1020 carbon steel billets. Nominal wall thickness of the nozzles and spacers is 0.25 inch (0.64 cm).

Test Facility

Testing will be conducted at CTL-IV, Cell 29 area, of the Santa Susana Field Laboratory. This facility is designed specifically for carrying out gaseous oxygen/gaseous hydrogen test firings at simulated altitude conditions with ambient temperature and temperature-conditioned propellants. The facility consists of an altitude simulation chamber which contains two independent test positions. One of these will be used for the high chamber pressure tests while the parallel position will be employed for the low chamber pressure tests described herein. A schematic flow diagram representing one of the test positions is presented in Fig. 54.

The altitude chamber is evacuated by a stream ejector supplied by a LOX-alcohol-water combustor which produces 42 lb/sec (19 Kg/sec) of vitiated

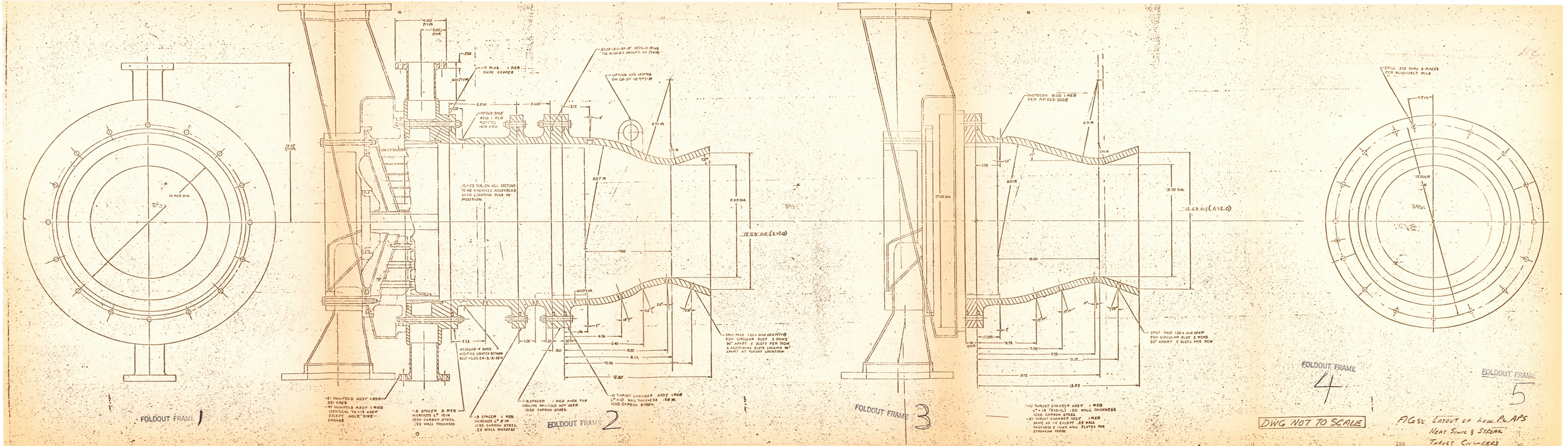

FIG 53 LAYOUT OF LOW PC APS HEAT SINK & STREAK THRUST CHAMBERS

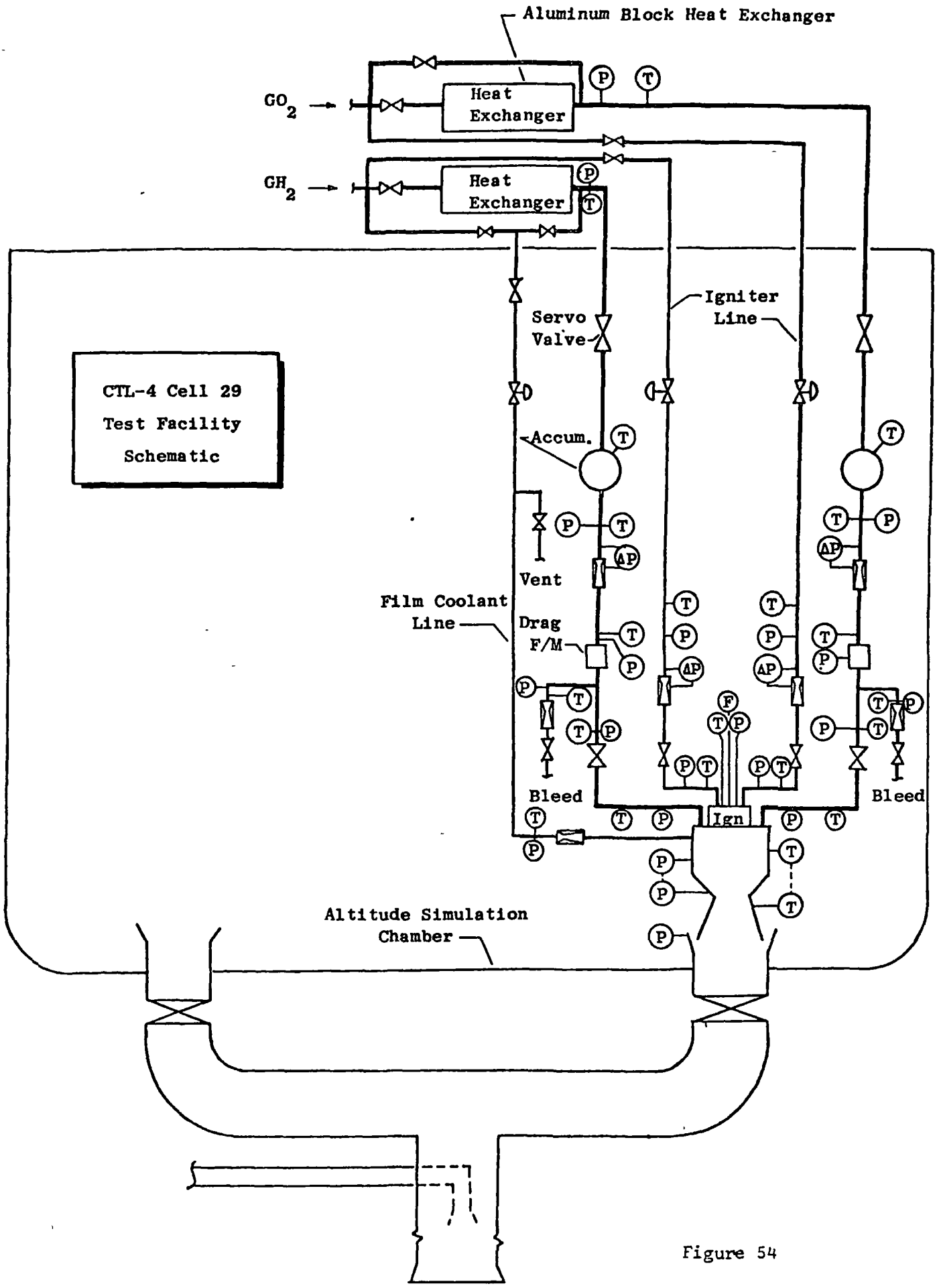
Aluminum Block Heat Exchanger
GO_2
Heat Exchanger
GH_2
Heat Exchanger
CTL-4 Cell 29
Test Facility
Schematic
Servo Valve
Igniter Line
Accum.
Vent
Film Coolant Line
Drag F/M
Bleed
Bleed
Ign
Altitude Simulation Chamber

Figure 54

steam at 350 psia (242 N/cm^2) and 960 R (533 K). The ejector is joined to two diffusers, one at each test position, and estimated duration of a single steam flow is 700 to 800 seconds. Several test firings will be programmed during each flow and two flows per test-day are possible.

While this test program will be conducted with ambient temperature propellants, the facility is capable of providing heated or chilled propellants. The required temperature conditioning is accomplished in separate heat exchangers which supply both test positions, with chilling by means of liquid nitrogen and warming by means of electrical resistance heaters. Bypasses are provided around each heat exchanger for ambient temperature propellant tests.

Each of the propellant flows to the low chamber pressure test position is separated into two parts: a 6-inch (15.2 cm) system to the injector and a 1-inch (2.5 cm) system to the igniter. Propellant pressurization levels at the injector inlets are maintained by means of servo-valves, and the igniter and coolant line pressures are controlled by dome regulators. The main and igniter propellant valves are high-response units. During the igniter evaluation phase of testing, sonic flow control devices will be incorporated in the facility operation, and the entire matrix of igniter flowrate and mixture ratio can be conducted without facility changes. By placing the sonic device immediately upstream of the igniter valve, the igniter start transient will approximate a pressure-fed system, such as the one used during the igniter only checkout tests.

Instrumentation

Sufficient pressure and temperature sensors are used to establish and monitor the system/hardware conditions. Transducer locations are shown schematically in Fig. 54. Data acquisition includes a high-speed digital system, an

oscillograph recorder, Brush recorders, and a high-frequency F/M magnetic tape recorder. Direct-inking graphic recorders will be used for system setup.

Data Reduction

The digital data tape, together with a program control tape (containing slice point information, control data, calibration factors, environmental data, etc.), are computer-processed by means of a scaling program which converts counts to engineering units. Programmed computer output consists of tables of time vs parameter values. These are printed out as either the instantaneous values at very short intervals during the firing (transient scaling program) or as average values over pre-specified time slices (steady-state scaling program), together with calibration factors, prerun and post-run zero and span readings, and related data. The same computer results are also machine-plotted and displayed at CRT outputs on appropriately scaled and labeled grids. The scaling program will be linked to another computer program which will include routines for on-line calculation of results derived from the primary data (such as propellant flowrates, mixture ratios, and uncorrected performance efficiencies). This will permit rapid evaluation of the effects of parametric variations in inlet conditions.

Status

The test plan for the low pressure thruster ignition tests was submitted and approved January 1971. The assembly was installed on the facility and initial facility checkouts have been completed.

(Subsequent to the end of the quarterly report period but during the writing of this report, the low pressure thruster igniter program was successfully completed. A summary of this program is presented in Table 24 . Ten

TABLE 24

PRELIMINARY LOW PRESSURE THRUSTER/IGNITER TEST RESULTS

Test No.	Thruster *			Igniter **			Results
	P_c psia	P_c N/cm^2	MR o/f	$\dot{W}_T$ lb_m/sec	$\dot{W}_T$ Kg/sec	MR o/f	
1	15	10.35	2.5	0.038	.017	1.5	Ignition Delay vs Igniter $\dot{W}$
2	15	10.35	2.5	0.039	.018	1.0	Igniter Delay vs Igniter MR
3***	15	10.35	2.5	0.039	.018	0.8	
4	15	10.35	2.5	0.039	.018	0.8	
5	15	10.35	2.5	0.020	.009	1.0	
6	15	10.35	2.5	0.020	.009	1.0	
7	15	10.35	2.5	0.020	.009	0.8	
8	15	10.35	2.5	0.019	.009	1.5	Simultaneous Valves
9	15	10.35	2.5	0.019	.009	1.0	Thruster/Igniter Response
10	15	10.35	2.5	0.010	.005	1.5	
11	10	10.35	2.5	0.018	.008	1.4	

* Nominal Thruster Conditions

** Actual Igniter Conditions

*** This test resulted in a thruster no-ignition. The test was repeated with successful ignition (Test 4). The non-ignition test is currently being investigated.

successful ignition tests were completed with spark igniter flowrates of 0.01 to 0.04 lb_m/sec (0.004 to 0.018 Kg/sec) or 0.25 to 1.0 percent of thruster flowrates and igniter mixture ratios of 0.8:1 to 1.5:1 (o/f). During four of these tests, the thruster response from electrical signal to 90 percent chamber pressure was demonstrated by signaling the thruster and igniter valves simultaneously.)

The low pressure spark igniter assembly has been made available to the Hydrogen/Oxygen APS Engine Contract NAS 3-14352. At the time of this writing, a total of 38 successful tests have been conducted on the low pressure spark igniter and complete thruster assembly.)

TASK III - IGNITION SYSTEM PRELIMINARY DESIGN

During Task III, the results of Task II testing will be used to conduct a preliminary design of a complete ignition system. This effort will be closely coordinated with the NASA Project Manager to ensure the latest available thruster designs are incorporated. The operational limits (propellant inlet temperature and pressure) and the required sequencing and geometric constraints obtained from the Task II tests will be major design input parameters.

The preliminary designs will be completed for the spark igniter and auto igniter for the high chamber pressure [300 psia (206.9 Newtons/cm^2)] application. The designs will include a layout of the propellant plumbing and the mechanical components and the operating characteristics and limitations will be delineated. System weight, volume, and propellant usage data will be calculated.

This task was not active during this report period.

TASK IV - REPORTING REQUIREMENTS

In addition to the monthly, quarterly and final reports, a program plan, design reports, and test plans are required in this task. A list of the submittals made to the LeRC Project Manager during the first quarter follows.

1. APS Igniter System Quarterly Technical Progress Narrative, ASR 70-460, August-October 1970.

2. Fourth Monthly Technical Progress Narrative, ASR 70-492, November 1970.

3. Fifth Monthly Technical Progress Narrative, ASR 71-16, December 1970.

4. Spark Igniter Test Plan, ASR 70-461, November 1970.

5. Auto-Igniter Design Report, ASR 70-476, December 1970.

6. Auto-Igniter Test Plan, ASR 70-490, December 1970.

7. Low Pressure Igniter/Thruster Test Plan, ASR 71-28, January 1971.

PROBLEMS

No major problems have occurred which will affect the overall program technical, schedule, or cost status. The overall program schedule and costs are approximately as planned.

WORK TO BE PERFORMED NEXT REPORT PERIOD

TASK I - IGNITER DESIGN AND FABRICATION

During the next report period, Task I spark igniter efforts will be devoted to the fabrication of the integrated spark/exciter unit. All other Task I efforts have been completed.

Additional resultant data from the spark plug studies and the resultant spark energy data from the hot-firing tests (Task II) have been reduced and evaluated. This information was used in the final design for the integral exciter unit and energy transfer circuit. The energy level (20 mj) voltage (10 KV) and spark frequency (200 cps) were key design inputs available in mid-January. Fabrication of long lead items has been initiated. Fabrication and checkout test are schduled to be completed the first week of March.

TASK II - IGNITER TESTS

During the next report period, Task II efforts will be devoted to low pressure thruster testing utilizing the low pressure spark igniter, and auto igniter "igniter only" testing.

A test series will be conducted utilizing the low pressure spark igniter from Task I and a low pressure thruster assembly to evaluate the effects of igniter flowrate and mixture ratio on thruster ignition delay. (The test program was described in detail in a preceding section.) This testing will be completed in early February.

The auto igniter "igniter only" testing (as described in a preceding section) will be completed in early February. Tests will be conducted to evaluate the auto-igniter operation over a range of propellant inlet conditions, including cold propellants.

The high pressure thruster test program planning will be initiated during the month of February and testing will be conducted in March.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT PROGRESS SCHEDULE

REPORT FOR MONTH ENDING: JAN. 1971

FORM APPROVED BUDGET BUREAU NO: 104-R0007

9 NASA Use Only

a NASA CODE

b PROJECT MGR

c EVALUATION DATE

d EXCEPTION CATEGORY

1 CONTRACT TITLE: Space Shuttle Auxiliary

2 CONTRACTOR (Name and address): Rocketdyne Division, North American Rockwell Corp. 6633 Canoga Avenue; Canoga Park, California 91304

3 CONTRACT NO: NAS3-14351

4 APPROVED (Contractor's Project Manager): [signature]

PREPARATION DATE: 15FEB71

5 NASA APPROVED SCHEDULE DATE

6 REPORTING CATEGORY	7 1970 J A S O N D	1971 J F M A M	8 TECH OBJECTIVE % COMP	e	f	g
TASK I IGNITION DESIGN & FABRICATION						
TASK II IGNITER TESTING						
TASK III IGNITION SYSTEM PRELIM. DESIGN						
TASK IV REPORTS AND PROGRAM MANAGEMENT						

NASA-C-63 (Rev 1-68)

NASA APPROVED SCHEDULE

CONTRACTOR'S WORKING SCHEDULE